Revista Ciencia en Desarrollo. Vol. 16 Num. 2. pp. 152 - 164
julio - diciembre

DOI: 10.19053/uptc.01217488.v16.n2.2025.17529

Artículo de investigación

Study of the electrical charge storage of Barium Titanate ($BaTiO_3$) a systematic review

Estudio del almacenamiento de carga eléctrica del Titanato de Bario ($BaTiO_3$), una revisión sistemática

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Recepción: 24-abril-2024 **Aceptado:** 13-febrero-2025 **Publicado:** 20-julio-2025
Cómo citar: Dionizio Solarte, S. A. *et al.* (2025). Estudio del almacenamiento de carga eléctrica del Titanato de Bario (BaTiO3), una revisión sistemática. *Ciencia En Desarrollo*, 16(2). doi: 10.19053/uptc.01217488.v16.n2.2025.17529

Abstract

This literature review article presents the state of the art of ferroelectric studies of Barium Titanate ($BaTiO_3$), a widely used ceramic material. Special emphasis is made on the different methods and techniques that have been developed to analyze the electrical polarization response of this material as a function of harmonic content and/or frequency, this characteristic is fundamental to understand its ferroelectric behavior. Also, amplifiers and sources that can be used in ferroelectric analysis are discussed, although they were not originally designed for this purpose. At the end of the article, a critical analysis of the current status of the study of the electrical polarization behavior of $BaTiO_3$ as a function of harmonic content and frequency is made. It is hoped that this literature review will contribute to promote new studies in this field and to improve the understanding of the ferroelectric properties of $BaTiO_3$.

Keywords: Electrical charge, harmonic content, frequency, sources and amplifiers.

Resumen

En este artículo de revisión bibliográfica se presenta el estado del arte de los estudios ferroeléctricos del Titanato de Bario ($BaTiO_3$), un material cerámico ampliamente utilizado. Se hace especial énfasis en los diferentes métodos y técnicas que se han desarrollado para analizar la respuesta de la polarización eléctrica de este material en función del contenido armónico y/o la frecuencia, esta característica es fundamental para entender su comportamiento ferroeléctrico. Asimismo, se discuten amplificadores y fuentes que pueden ser utilizados en el análisis ferroeléctrico, aunque originalmente no fueron diseñados para tal fin. Al final del artículo, se realiza un análisis crítico del estado actual del estudio del comportamiento de la polarización eléctrica del $BaTiO_3$ en función del contenido armónico y frecuencia. Se espera que esta revisión bibliográfica contribuya a promover nuevos estudios en este campo y a mejorar la comprensión de las propiedades ferroeléctricas del $BaTiO_3$.

Palabras Clave: Carga eléctrica, contenido armónico, frecuencia, fuentes y amplificadores.

E-ISSN: 2462-7658

1 Introduction

A ferroelectric material is a dielectric that presents a spontaneous polarization, even in the absence of external electric field [1], the electric polarization is the vector field that expresses the density of permanent or induced dipole moments in a dielectric material, this parameter is perhaps the most important factor, since it allows characterizing a ferroelectric material by means of the ferroelectric hysteresis curve. Since the discovery of the phenomenon of ferroelectricity in the 19th century, a large number of multiferroic materials have been discovered that combine this phenomenon (ferroelectricity) with ferromagnetism. Ferroelectric materials have become the object of study of many investigations related to their construction, production and analysis [1, 2, 3]. The techniques used for the characterization of this type of materials have evolved due to new trends in electronic instrumentation, which allow innovating measurement and control strategies, with the objective of a ferroelectric analysis in terms of electric field, frequency, harmonic content, amplitude of the stimulation signal, temperature, pressure and magnetic field [4-8].

A great impulse for ferroelectricity research was given with the fabrication of Barium Titanate ($BaTiO_3$) and Lead Titanate ($PbTiO_3$) which gave rise to a new variety of ferroelectric materials [4-7]. Nowadays, multiferroic materials are known, which are still little explored and present a gap in the study of these effects in terms of harmonic content and frequency [1, 4, 5]. The results presented in [6-10] suggest $BaTiO_3$ as a fundamental mixing element, for the construction of new materials with multiferroic effects. In addition, this material is used for the calibration of commercial equipment such as those offered by Radiant Technologies and the TF 2000 analyzer oriented to the study of ferroelectric hysteresis in new non-conventional materials.

The importance of studying the phenomenon of ferroelectricity, apart from understanding the electrical properties of solid state materials, is the ability to store information due to the presence of an oscillating electric field produced by an alternating voltage that energizes a capacitor of parallel plates or coplanar contacts; whose dielectric is one or more solid materials containing this physical property [6]. $BaTiO_3$ is a fundamental basis as a ferroelectric dielectric for the construction of electronic devices [7, 8, 9], since it has the property of storing information in logical states of matter (bits of information), this has motivated efforts to find and produce digital memories that have lower power consumption, lower cost and higher density of data accumulation, such as random access memories or flash memories; although, with limitations related to electrical charge losses, causing unwanted data erasure and general reliability issues associated with memory capacity. Another incursion of $BaTiO_3$ is in the construction of photovoltaic cells due to its Perovskite-type structure [10], and applications in which $BaTiO_3$ is being explored in the reconstruction of bone tissues as indicated in [11]. Considering all the above, it is essential to have a broad knowledge about how $BaTiO_3$ electrically responds to periodic extinction signals with different frequencies and harmonic contents. It turns out that this ceramic material is the fundamental basis for research on the effect of ferroelectricity, especially when it comes to exploring new materials with multiple functions for the creation of electronic devices that are related to this very elementary phenomenon. In this review, we explore different studies that have been developed on how $BaTiO_3$ behaves electrically when subjected to periodic excitations with different harmonic shades.

2 Methods and materials

A systematic review of the literature available in academic databases was carried out covering the period from 2004 to 2023. This review focused on two specific topics: i) The ferroelectric properties of $BaTiO_3$ versus harmonic content and frequency, and ii) Engineering: sources and amplifiers for ferroelectric analysis. The methodology employed follows the approach proposed in [12, 13, 14] and has been adapted to the particular context of the present investigation.

2.1 Literature review (databases)

To perform the systematic literature review, search strings related to the two particular topics were considered: i) Ferroelectric properties of $BaTiO_3$ versus harmonic content and frequency, and ii) Engineering: sources and amplifiers for ferroelectric analysis. With this approach, 8 academic database platforms such as Academic Google, SciencieDirect, researchgate, springer, iopscience, jstage and Wiley Online Library were used, as shown in Figure 1.

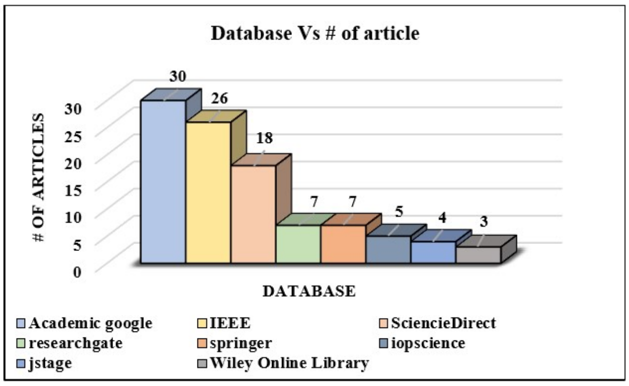

Figure 1: Number of articles per database.

2.2 Inclusion and exclusion criteria

For the selection of articles, inclusion and exclusion criteria were established based on the methodologies applied in [12, 13, 14] and adapted to the context of this research. The chosen criteria are shown in Table 1.

Considering the above criteria, 68 articles were considered relevant. The 68 studies were fully analyzed and examined and applying exclusion criteria, 60 primary articles were obtained as shown in Table 2.

2.3 Taxonomy (Selection of categories and topics)

The following taxonomy is used to perform a detailed analysis of ferroelectric studies of Barium Titanate ($BaTiO_3$), with a particular focus on the electrical polarization response in relation to harmonic content and frequency, as well as on the adaptation of amplifiers and sources to perform this analysis, this taxonnomy is present in the table 3.

This taxonomy, based on these characteristics, allows the specific properties of $BaTiO_3$ to be explored and presented in relation to the electrical polarization response as a function of harmonic content and/or frequency, as well as the adaptation of measurement equipment for this or other purposes.

3 Analysis and results

This section is structured in two topics in which the taxonomy explained above is included:

- **Ferroelectric properties of $BaTiO_3$ versus harmonic content and frequency**: This thematic area focuses on the general study of the ferroelectric properties of barium titanate ($BaTiO_3$), with special emphasis on its electrical polarization as a function of harmonic content and frequency. The characterization of the material under different conditions is addressed, including the influence of frequency and harmonics on its ferroelectric behavior.
- **Engineering; sources and amplifiers for ferroelectric analysis**: This area focuses on the development and research of the engineering necessary for the characterization of ferroelectric materials. The available instrumentation, methods and techniques are analyzed, including sources and amplifiers that meet the requirements for the analysis of these materials. The latest technologies and advances in this field are explored, with the objective of optimizing the measurement of ferroelectric properties. This division focuses on grouping the topics more specifically according to the properties of $BaTiO_3$ and the engineering related to sources and amplifiers.

3.1 Ferroelectric properties of $BaTiO_3$ versus harmonic content and frequency

In recent decades, ferroelectric parameters including electric polarization, electric field, electric permittivity, loss factor and polarization fatigue have been investigated in more detail. These parameters affect the measurement of the sample and have led to the creation of new materials at nanometer scales [15] and [16]. As a result, new electronic devices with improved physical properties have been developed. Such parameters are a function of the frequency, amplitude and harmonic content of the signal that stimulates the material, for this reason the research of Yang Li [17] where they work $BaTiO_3$ ceramic to achieve better energy storage performance due to its high Pr and low dielectric breakdown field strength hinders the development of miniaturization and lightness of power electronic equipment. Therefore, a two-step strategy including adjusting the ratio of chemical elements to modify the microstructures and optimizing the preparation process to improve the electrical breakdown strength has been proposed to greatly improve the energy storage performance of lead-free ferroelectric ceramics. In particular, the $(Ba_{0.65}Sr_{0.245}Bi_{0.07})_{0.99}Nd_{0.01}TiO_3$ (BT-SBT-NdVPP) ceramic, where a very high energy storage density of 4.2 J/cm3 under 460 kV/cm is obtained, and stability in temperature (30 ~ 100 °C) and frequency (10 ~ 400 Hz) ranges under 300 kV/cm are quite good. In addition, this research not only significantly improves the energy storage performance of BT-based ceramic, but also provides a reference for the preparation of dielectric ceramic with high quality, which could have great potential for practical industrial application.

Other related works, are [18] and [19], where they investigate polycrystalline ceramics, which improves the behavior in the presence of electric field; it was found that the phase changed from rhombohedral in $BiFeO_3$-rich compositions to pseudo cubic with medium $BaTiO_3$ content. The room temperature dielectric permittivity increased with increasing $BiFeO_3$ content regardless of the phase structure, except for a small dielectric permittivity peak observed when the $BiFeO_3$ concentration is medium. Normal ferroelectric loops and large electric field-induced strains were observed for $BiFeO_3$-$BaTiO_3$ ceramics. $BiFeO_3$-$BaTiO_3$ is shown to be a promising candidate for high temperature ferroelectric applications, the frequency dependence of the high temperature dielectric properties suggests that $BiFeO_3$-$BaTiO_3$ is a ferroelectric relaxor, these works study the ferroelectric hysteresis behavior of this material versus frequency variation, but not as a function of harmonic content.

Another compound $BaTiO_3$ is worked with is $BiYbO_3$ as shown in the paper by Zhengbo Shen et al [20] in which they prepare (1-x)$BaTiO_3$-x $BiYbO_3$ type solid solutions with Perovskite type structures and x=0.00~0.20 concentration. Dielectric measurements revealed a gradual change from normal ferroelectric behavior to highly diffusive and dispersive relaxing characteristics, where the phase transition temperature changed to higher temperature with increasing frequency. With increasing $BiYbO_3$ content, the nonlinearity of the ceramic weakened. The in-grain ceramic was characterized by high polarization maxima and low remanent polarization, exhibiting thin P-E hysteresis loops when the sample was stimulated with a triangular wave at 1Hz. The results demonstrated that the ceramic was a promising lead-free relaxor material for energy storage application. Another application of $BaTiO_3$ is in liquid crystal displays as shown in the paper by Indrani Coondoo [21], where they analyzed the dielectric and polarization properties of a low concentration ferroelectric nano-particle ($BaTiO_3$) suspension in a FLC (ferroelectric liquid crystal) host. It is found to exhibit dielectric memory and enhanced spontaneous polarization values compared to pure LC (liquid crystal). The effect is explained against the contribution of permanent polarization of the particles interacting with the LC molecules. It is concluded this type of compounds can be used to improve the performance of liquid crystal displays and related optical communication applications. The two previous studies lack numerical results because the values can be extracted from the graphs and were not described quantitatively, on the other hand, none of the articles delves into the ferroelectric behavior against different signals with various harmonic contents.

Frequency dependent ferroelectricity studies are presented with Das et al [22] where they studied on the structural, magnetic and ferroelectric properties of Ni doped barium titanate. Ceramic samples of $BaTiO_3 - xNi_xO_3$ (here, x = 0,

Table 1: Selection, inclusion and exclusion criteria.

Selection criteria	
Inclusion	*Exclusion*
Studies related to the electrical behavior of $BaTiO_3$ against periodic excitations with different harmonic contents and frequencies.	Works older than 20 years
Studies related to instrumentation for ferroelectric analysis (voltage sources, voltage amplifiers, industrial equipment, Sawyer-Tower Circuit, etc...).	Works such as degree projects, reports and guides of experimental techniques.
Studies containing techniques and methods for the ferroelectric and electrical characterization of $BaTiO_3$ in new materials.	That the research lacks information to document it under the context of the research.

Table 2: Relevant studies for the research based on selection criterio.

Databases	*Studies*			
	Found	Not repeated	Relevant	Primary
Academic google	30	23	18	18
IEEE	26	22	18	12
SciencieDirect	18	18	17	16
researchgate	7	5	5	4
springer	7	5	4	4
iopscience	5	4	2	2
jstage	4	3	2	2
Wiley Online Library	3	3	2	2
Total, articles	100	83	68	60

Table 3: Taxonomy categories and topics.

Categories and Topics		
Category	*Category Definition*	*Category Topics*
X	Ferroelectric Properties and Engineering.	X.1= Polarization Hysteresis and/or Coefficient of Permittivity X.2= Other Applications.
Y	Harmonic Content and/or Excitation Frequency.	Y.1= Variable Harmonic Content and/or Variable Frequency. Y.2= Fixed Harmonic Content and/or Frequency.
Z	Adaptation of Sources and Amplifiers.	Z.1= Selection of Appropriate Amplifiers and Sources. Z.2= Selection of Appropriate Amplifiers and Sources.

0.05, 0.1 and 0.15) were prepared by solid state synthesizing technique. Ferroelectricity was observed for all samples at room temperature, but was reduced by doping with Ni. It is observed that the value of the maximum polarization as well as the shape of the hysteresis loops are highly dependent on the Ni doping concentration, the shape of the P-E loops was highly dependent on the procedure, therefore, the measurement was carried out at three different frequencies, that is at 1 kHz, 10 kHz and 100 kHz. From the P(E) loops, it is observed that the shape of the loop does not change with frequency, but the values of remanent polarization (Pr) and coercive field (Er) do. Therefore, the presence of an electrical bias exists in all compositions according to typical ferroelectric materials; this article evidences the changes of the remanent polarization and coercive field of ferroelectricity in terms of frequency, but not as a function of harmonic content. In the paper by Ming Ding Li et al [6] the lead-free ferroelectric ceramic (1-x)$BaTiO_3 - xBi(Mg_{1/2}Ti_{1/2})O_3$ (x = 0.0 - 0.07) was synthesized by conventional solid-state reaction method and the correlation of structure, dielectric, ferroelectric and impedance properties was investigated. It was found that dielectric relaxation behavior at high temperature occurs in all samples. On the other hand, with increasing BMT (bismuth magnesium titanate) contents, it was found that the P-E (electric field) (polarization) loops taken at fixed electric field amplitudes such as 1.41eV, 1.37eV, 1.28eV, 1.21eV and 1kHz became thinner. The temperature dependence of the P-E loops for 0.98BT-0.02BMT ceramics clearly showed the transition process from ferroelectric to relaxed ferroelectric, a limitation is revealed in the research which lacks the study of these effects as a function of different frequencies, stimulus signal amplitudes and harmonic content, since it works with Radiant equipment which limits this type of study with these parameters.

Studies on ferroelectricity at low frequencies is presented by Guoqiang Zhang et al [23], reveal the effect of space charge induced interfacial polarization on dielectric losses, in this work, bipolar and unipolar electric displacement loop tests (related to electric polarization) vs electric field (D-E) were performed; although, analyses of these variables are not shown due to the harmonic content of the excitation signal. Other fundamental variables in the study of ferroelectricity is temperature and pressure, as shown in [24], where $BiFeO_3$ and $BaTiO_3$ ceramics and their multiferroic and thermal properties at different pressures were investigated. The composite films show high ferroelectric saturation polarization of more than 70 uC/cm^2. The multilayers show the highest magnetization of 2.3 emu/cm^3, due to the magnetic moments at the interface and the exchange coupling of the included weak ferromagnetic phases. On the other hand, this composite shows magnetoelectric coupling of the $BaTiO_3$ - $BiFeO_3$ films.

There are studies where they mix three compounds to form a new material with more pronounced physical properties and with more capacity, as shown in [15] where the compound (0.95-x)$BaTiO_3$-0.05$BiYbO_3$-x$BiFeO_3$ with concentrations of x = 0, 0.01, 0.02, 0.04, considering dielectric measurements with different frequencies up to MHz, revealed that all samples exhibited weak relaxation behavior. Moreover, the minimum dielectric constant of the BFO-doped ceramic was obtained at x=0.01. Ferroelectric measurements indicated thin hysteresis curves even though the composite was excited with 500Hz and an electric field up to 10kV/cm. The remanent polarization (Pr) and coercive field (Ec) of (0.95-x)BT-0.05BY-xBFO first decreased and then increased with increasing x, the minimum values were obtained at x=0.01. To conclude, this study shows the strong tendency of $BaTiO_3$ to attribute the effect of ferroelectricity together with other materials, but there is a lack of analysis of how much the ferroelectric hysteresis can affect the new material in the presence of periodic excitation signals with different harmonic contents.

Other studies where they work $BaTiO_3$ ceramics in thin films is that of authors Yoonho A. and Jong Y. [25] where they disclose the deposition rate dependent ferroelectric properties of $BaTiO_3$ thin films fabricated through pulsed laser deposition. $BaTiO_3$ thin films were epitaxially grown on single-crystalline Rh (001) substrates. The $BaTiO_3$ thin films exhibited deformed tetragonal structures with c / a ratios of 1.05 (0.02 nm/pulse) and 1.03 (0.3 nm/pulse), depending on the film deposition rate. The increased tetragonality improves the ferroelectric properties of the films. In addition, their deposition rate determines their leakage current and bandgap energy. Using scanning probe microscopy, we observed the surface morphologies and ferroelectric domain structures of the films. In addition, a ferroelectric domain analysis based on the Landau-Lifshitz-Kittel scaling law indicated that a reduction in the growth rate leads to an increase in the domain size and domain wall energy of the $BaTiO_3$ thin films. Finally, it was shown that the optical bandgap of $BaTiO_3$ thin films is related to their tetragonality. Studies such as those of Nan Ma et al [26] report intrinsic properties on the temperature dependence of the photocurrent and its relation to the ferroelectric polarization. The photocurrent of $BaTiO_3$ Ceramics is highly temperature dependent, which can achieve an enhancement of 121.9±179.6% at low temperature (80-240 K) compared to room temperature. The photocurrent enhancement is associated with the ferro-piro-phototronic effect, which is evidenced by enhanced ferroelectric polarization and activation of shallow trap levels at low temperature, which can be used to detect 405 nm light at low temperature. This research provides a potential approach to boost the photocurrent of ferroelectric ceramics and enable the development of a wide range of optoelectronic devices.

On the other hand, the evolution of dynamic hysteresis in epitaxial ferroelectric $BaTiO_3$ (BTO) thin films prepared by pulsed laser deposition is also investigated as seen in [27]. The study focuses on the hysteresis behavior as a function of electric field amplitude and frequency in BTO films.The researchers used methods of preparing BTO thin films by pulsed laser deposition and examined how the dynamic hysteresis evolves with electric field amplitude and frequency. They observed a transition in hysteresis behavior from low frequency to high frequency in BTO films, suggesting a change in domain motion dynamics at different frequencies. A theoretical model was analyzed to explain the scaling behavior of dynamic hysteresis in BTO films. Good agreement was observed between the model results and the experiments performed, suggesting a deeper understanding of the relationship between electric field amplitude, frequency and hysteresis in ferroelectric films. In conclusion, the study provides valuable information on the evolution of dynamic hysteresis in BTO thin films and highlights the importance of considering both electric field amplitude and frequency when studying ferroelectric behavior in these materials. The results obtained contribute to the understanding of the ferroelectric properties in BTO thin films and may have implications in the design of ferroelectric devices for various applications.

Novel materials exhibit improved properties of $BaTiO_3/LaNiO_3$ ferroelectric superlattices compared to pure $BaTiO_3$ films as suggested by Jun Liang Lin et al [28] who present a study the preparation and characterization of $BaTiO_3/LaNiO_3$ ferroelectric superlattices with different stacking periods by pulsed laser deposition (PLD). It is highlighted that the BTO/LNO superlattices show significantly improved ferroelectric and dielectric properties compared to pure BTO films. The arguments presented in the paper focus on the fact that, in addition to the strain effect, the accumulated oxygen vacancies in each ultrathin LNO layer can change the depolarization field and reduce the leakage current in the superlattices. It is suggested that the use of ultrathin metal oxide layers as the constituent material of ferroelectric superlattices is a feasible and effective method to improve the properties of superlattices. The study indicates that BTO/LNO superlattices exhibit remarkably enhanced ferroelectric polarization and dielectric constant, suggesting significant potential for applications in electronic and energy storage devices. The importance of controlling the properties of ultrathin metal oxide layers to optimize the performance of ferroelectric superlattices is highlighted. In summary, the article provides detailed insight into the preparation, characterization and improved properties of $BaTiO_3/LaNiO_3$ ferroelectric superlattices, highlighting the influence of oxygen vacancies on the improvement of electrical properties. This study contributes to the advancement in the design and development of ferroelectric materials with potential applications in emerging technologies.

Studies on the electrocaloric effect (ECE) in *La*-doped $BaTiO_3$ ferroelectric ceramics, which is a phenomenon involving a change of temperature and entropy in a polar material upon application or removal of an electric field is worked out in

[29], The authors argue that La doping can reduce the Curie temperature (Tc) of $BaTiO_3$ and increase its ferroelectric polarization, leading to a higher electrocaloric effect near room temperature. To demonstrate this, they prepare $Ba_{1-x}LaxTiO_3$ samples with different La concentrations and measure their structural, morphological, dielectric and ferroelectric properties. Then, they calculate the adiabatic temperature change (ΔT) using Maxwell's relation from the polarization data. The authors conclude that La doping is an effective and reliable method to achieve the room temperature electrocaloric effect in lead-free ferroelectric materials. In particular, they find that the sample with x = 0.04 has a Tc of 303 K and a ΔT of 1.81 K under a field of 60 kV/cm, representing a large electrocaloric strength of 0.30 K-mm/kV. The authors suggest that this material has great potential for application in solid-state cooling technologies. The article also provides information on the mechanism of the electrocaloric effect, the influence of the Goldschmidt tolerance factor on the stability of the perovskite structure, the comparison of the electrocaloric effect with other ferroelectric materials reported in the literature, and the limitations and perspectives of the work performed.

Other properties are analyzed in the article by Alicia Manjo'n-Sanz et al [30] which deals with the study of the structural and electromechanical properties of the lead-free piezoelectric system (1 - x)$BaTiO_3$ - (x)$BiInO_3$ (BT-BI) in the range $0.03 \leq x \leq 0.12$. The authors argue that this system exhibits a gradual structural phase transition, where the structure changes from tetragonal (P4mm) to a phase coexistence region (P4mm + R3m) and finally to cubic (Pm3m + R3m) as the BI content increases. They also argue that the electrical properties change from ferroelectric to relaxor ferroelectric, which is evidenced by the temperature and frequency dependence of the maximum dielectric permittivity. They further argue that the critical composition x = 0.065 shows an enhancement of the piezoelectric properties, with a maximum strain of 0.104% and an effective piezoelectric coefficient (d33*) of 260 pm/V, due to the ferroelectric-relaxor ferroelectric phase transition. The authors conclude that the BT-BI system is a promising candidate for lead-free piezoelectric actuator applications, as it exhibits moderate electromechanical response and superior thermal stability compared to other BT-based systems. However, they also conclude that the polarization extension mechanism predicted in the literature is not present in this system, but rather a polarization rotation mechanism.

Studies where porosity-induced structural, dielectric and ferroelectric properties of $BaTiO_3$ are modified by the authors Leontin Padurariu et al [31] investigated the effect of the addition of PMMA (polymethylmethacrylate) spheres as sacrificial templates to produce porosity in the range of 4%to 26% by volume in $BaTiO_3$ ceramics. They studied the influence of porosity on the phase composition, morphology, density, dielectric constant, polarization, tunability, and P(E) loops of the resulting ceramics. The authors found that PMMA-induced porosity affects both the intrinsic and extrinsic properties of $BaTiO_3$ ceramics. In particular, they observed that porosity favors tetragonal symmetry over orthorhombic symmetry, reduces the internal stress, decreases the dielectric constant and polarization, and modifies the hysteretic character of the dielectric and ferroelectric response. They also proposed a Landau-based model to explain the possible electric field-induced structural phase shift in the denser ceramics.

A study was conducted on the use of electrical stimulation to guide stem cell differentiation on an electroactive polymer substrate that mimics the structure of bone according to authors Asish Kumar Panda et al [11]. The researchers employed different types of electrical waveforms to stimulate human mesenchymal stem cells (hMSCs) on a poly (vinylidene-difluoride) barium titanate ($BaTiO_3$, BT) composite. The results revealed that electrical stimulation by direct current, square wave and biphasic waveforms induced osteogenesis of hMSCs at different stages of differentiation. The study also examined the underlying biophysical principles of bioelectrical regulation of osteoinductivity and its potential clinical application to promote bone tissue regeneration. The researchers emphasized that although electrical stimulation is used clinically for tissue regeneration and improvement of neuromuscular functionalities, the nature of electrical waveforms and their role in regulating osteogenesis have not yet been scientifically explored. In summary, this study is significant because it presents a novel strategy for regulating osteogenesis by electrical stimulation, eliminating the need for external biochemical inducers of differentiation.

Studies such as Richa Sharma et al [32] focus on multiferroic materials combining $BaTiO_3$ as the ferroelectric phase and $CoFe_{1,8}Zn_{0,2}O_4$ as the ferrite phase. These composites were fabricated by the solid-state reaction method. The study used techniques such as X-ray diffraction (XRD) to confirm the phase purity and structure formation, and scanning electron microscopy (SEM) to study the morphology of the composites. An increase in grain size with ferrite content was observed. Variations of the dielectric constant and loss tangent with temperature and frequency were investigated, showing an increase of the dielectric constant with ferrite fraction and the appearance of two peaks associated with ferroelectric to paraelectric phase transitions. AC conductivity was also analyzed to understand the conduction mechanism. The main conclusions include the significant effect of ferrite content on the dielectric, electrical and magnetic properties of the composites, as well as the observation of good simultaneous ferroelectric and ferromagnetic properties in all composites. The importance of these multiferroic materials in various technological applications is highlighted.

The article by Marin Cernea et al [33], focuses on the investigation of the electrical properties of holmium-doped $BaTiO_3$ obtained through a sol-gel combustion method. The researchers prepared $Ba_{0.97}Ho_{0.03}TiO_3$ ceramics and carried out a detailed analysis of their structure, microstructure, dielectric properties and ferroelectric behavior. It was observed that the ceramics exhibited high dielectric constant, low dielectric loss, and specific polarization and coercive field values. It was highlighted that the material behavior was influenced by the amphoteric character of the Ho3+ ions. The study used various characterization techniques such as X-ray diffraction analysis, scanning and transmission electron microscopy, as well as high-resolution transmission electron microscopy. Dielectric properties were evaluated over a temperature range from 0 to 160 °C at different frequencies. In addition, electrical measurements were performed in metal-ferroelectric-metal configuration to determine the electrical properties of the material. In conclusion, the article highlights the importance of holmium doping in $BaTiO_3$ to improve its dielectric and ferroelectric properties. The results obtained provide valuable information on the electrical behavior of this doped material and its potential application in electronic devices.

Authors such as Qin Zhou et al [34] developed a lead-free piezoelectric and ferroelectric ceramics with elevated Curie temperature by adding Ga to $BiFeO_3$-$BaTiO_3$. The objective was to improve the electrical and piezoelectric properties of the materials. The experimental process involves the preparation of ceramic samples by processing metal oxide powders, followed by sintering and characterization of the properties. The results show that the addition of Ga favors the increase of grain size, densification and improvement of piezoelectric properties. A pure crystalline structure is observed and well saturated P-E hysteresis loops are obtained. In conclusion, Ga modification on BGFx-BT ceramics shows potential for high temperature applications, highlighting the importance of this approach in the development of advanced piezoelectric materials. Other studies such as the one by the authors of [35] prepared single-phase ceramic samples with different percentages of $BaTiO_3$ and $BaNi_{0.5}Nb_{0.5}O_3$. X-ray diffraction analyses showed that the samples with x = 0, 0.01, 0.02 and 0.04 have a tetragonal crystal structure, while those with x = 0.03 and 0.05 are cubic. The average grain size of all samples was calculated by scanning electron microscopy. Raman and photoluminescence spectra were recorded at room temperature. Electrical hysteresis loops indicated that the coercive field, remanent polarization and energy losses depend on the x-value. The electric strain field was studied and it was observed that the piezoelectric properties improve with increasing x. Overall, the results obtained in this study are promising for future applications of these ceramics.

A study on the asymmetric switching of ferroelectric polarization in a 58 nm thick $BaTiO_3$ film has been performed as shown by the authors Kazuhide Abe et al [36]. The film was prepared by magnetron sputtering on a $SrRuO_3/SrTiO_3$ substrate. The $BaTiO_3$ film was found to have a c-axis oriented normal to the surface that is 3% longer than that of the bulk due to the lattice mismatch between the materials. When applying positive and negative voltage pulses of the same amplitude, an asymmetric response in the transient current was observed. Although the switching charge densities were equal for both polarities, the switching time was longer and the peak current was lower for the positive response. From the transient current analysis, asymmetric polarization switching was attributed to the discrepancy in coercive voltages between the polarities.

In this study [37], ferroelectric superlattice structures were fabricated by pulsed laser deposition of alternating $BaTiO_3$ and $SrTiO_3$ layers on Pt 111 $/TiO_2/SiO_2/Si$ 100 substrates. X-ray diffraction analyses showed the presence of superlattice reflections in a range of layer thicknesses between 6.4 and 20 nm. Depth profiles revealed a periodic concentration of Ba and Sr throughout the film. The films also showed clear size-dependent ferroelectric characteristics, with spontaneous and remanent polarization increasing and then decreasing as the periodicity decreases. It is suggested that this behavior may be attributed to competition between the size effect and the long-range ferroelectric interaction. The temperature dependence of the spontaneous and remanent polarization showed a single ferroelectric phase transition, with an estimated Curie temperature of approximately 316 K. In summary, the ferroelectric superlattices form an artificial material with averaged behavior of the two parent systems. To conclude, the paper [38] analyzes the repolarization of $BaZrO_3/BaTiO_3$ ferroelectric superlattices, focusing on the switching processes and domain boundary motions. How temperature changes affect the spontaneous polarization near the phase transition temperature is discussed, and two stages in the switching processes of the synthesized superlattices are identified. It is observed that the threshold field separating the activation and non-activation stages of switching varies with temperature in the superlattices.

3.2 Engineering: sources and amplifiers for ferroelectric analysis

There are studies where the instrumental architecture plays an important role in the understanding of the ferroelectricity phenomenon, this because of several factors, among them the costly of an industrial equipment, such as the Radiant, for ferroelectric analysis; for this reason electronic systems have been developed that facilitate the characterization of the different parameters of ferroelectricity such as the research of Zhang Bin [39], who developed an accurate broadband fractional operator model for nonlinearities of a piezoelectric ceramic. The model allows in particular to predict the evolution of the dielectric polarization as well as the mechanical displacement of the test sample and this whatever the type of stimulation (pure mechanical stress, electric field and even hybrid electric/mechanical excitation). These models are necessary to optimize a mechanical or electrical voltage waveform and to obtain higher efficiency of energy recovery systems. The use of the model allowed to perform very accurate predictions up to 1Hz for piezoelectric materials, the model has strong limitations when working at too low or too high frequencies (MHz).

Another study of instrumentation for ferroelectric measurement is that of Ramirez et al [40] where an automated installation was developed for measurements of hysteresis loops in ferroelectric materials, compensating the currents not produced by ferroelectric switching; in addition, the installation allows measuring the aging and fatigue of the samples. The results exposed by the developed system were compared with the Radiant, industrial equipment, for the PLZT ceramic (lanthanum lanthanum lead zirconium titanate) at a fixed frequency and amplitude, a good approximation of the ferroelectric parameters is determined, although the Radiant does not work with the S-T (Sawyer-Tower) circuit; the proposed system presents limitations outside the audible bandwidth so it is limited to work in a frequency range of 20Hz to 20kHz with a maximum amplitude of 2500V AC.

An instrumental architecture for ferroelectric measurement proposed in [41] shows an automated ferroelectric hysteresis loop measurement system that was developed under the LabView environment. The system provides a function to obtain nonlinear bias current from measured current data, which is important to properly estimate the ferroelectricity of a dielectric, especially for one with high electrical loss. In addition, the relationship between the nonlinear bias current density and the external electric field of a ferroelectric reveals more information that is useful for investigations of polar order and/or ferroelectric characteristics; this measurement system presents problems in handling high voltage amplitudes at high frequencies, making large impedance dielectrics impossible to analyze. Another study that incorporates the LabView tool is that of Ramirez et al [42], where they present a new facility to obtain the hysteresis loops with a signal generator developed with a PSoC (Programmable System-on-Chip), a programmable DAQ (Data acquisition) coupled to a computer and a new high voltage amplifier that improves the characteristics of the previously developed facility. As a result, a general scheme of instrumental installation for ferroelectric measurement with different measurement temperatures was obtained, a presentation interface was developed by means of the LabVIEW tool, having the instrumentation arranged for the measurement, measurements of the hysteresis loop were performed, as well as fatigue and/or aging of ceramic samples developed, obtaining partial loops of hysteresis of the ceramic at different electric fields, frequencies and temperature; Hysteresis curves were also obtained at different excitation amplitudes. In addition, a thermal treatment is found to measure the aging of the ferroelectric hysteresis of the ceramic when it has been stimulated with a sine wave of 2kV amplitude at 60Hz.

It is important to study ferroelectric phenomena at high frequencies and not only at low frequencies, since at high frequencies the phenomenon called electronic polarization arises, as in the study of Gallo [43] which consists of the implementation of a dielectric characterization technique of ferroelectric ceramic materials at microwave frequencies, that is, to determine their dielectric constant and the losses associated with the propagation of electromagnetic waves (loss tangent, delta tangent) with frequencies up to 8.5 GHz. The dielectric characterization reveals a relative dielectric constant of 20, a rather promising result. However, the dielectric loss, despite not reporting optimal levels (delta tangent = 0.001), conforms to results reported in similar studies. On the other hand, Rodriguez et al [44] implemented a system to measure ferroelectric properties using a potentiostat/galvanostat (POT/GAL) in a modified Sawyer-Tower circuit. A data acquisition board and a personal computer were used to remotely control the POT/GAL. The POT/GAL was used due to its very high input impedance to obtain the hysteresis cycles of ferroelectric samples. Software was developed to fully control the POT/GAL, as well as the amplitude, frequency and type of signal applied to the sample by means of the Sawyer-Tower circuit; an oscilloscope was used as an interface for the acquisition of the signals to the PC. This work allowed obtaining the hysteresis cycles of the spontaneous polarization versus electric potential and displays the values of the coercive potential and remanent polarization. To check the functionality of the system, ferroelectric capacitors of $Pb(xZr(1-x)Ti)O_3$ material also known as PZT (4,000-10,000 um of area and 255 nm thick) were characterized at different potential (1-9 volts) and frequency (1-45 Hz) and the results were compared with the measurements in a Radiant Technologies equipment, resulting in good agreement.

An important device in a ferroelectric characterization system is a high voltage AC source with gain, frequency and waveform regulation. For this reason, research on the design of voltage sources with these particularities is deepened, as proposed by Ghisu et al [45], where a new linear amplifier with a large integrated high voltage bandwidth is presented. This linear amplifier presented advantages compared to high-voltage digital pulsers, such as lower harmonic distortion and higher ability to generate complex and arbitrary waveforms. The results show that the amplifier employs a current feedback technique that overcomes the bandwidth gain limitation of a conventional voltage feedback amplifier.

Gao Jingxiang et al [46] have proposed a Z-source based high-frequency AC/AC converter, which consists of an input filter circuit, an inductor, an input cycle converter, a high-frequency transformer, an output cycle converter, a control switch, and an output filter. Experimental results demonstrate that the converter can effectively handle output signal frequency conversion, high-frequency operation, electrical isolation and load adaptability. This work establishes a key technical basis for the development of intelligent universal transformers (IUTs), sinusoidal ac voltage stabilizers and voltage regulators. Please provide feedback on the potential applications and advantages of this converter technology. Similar work is presented in [47], where a converter is presented that inherited all the advantages of the traditional single-phase Z-source AC/AC, which has control over inverting boost and phase angle maintenance. Simulation and experimental results verified that the converter has lower input current total harmonic distortion and higher input power factor compared to the conventional single-phase Z-source AC/AC converter. Subsequently Hafiz et al [48] propose several ZS-based HFTI AC/AC converters, taking the quasi-ZS (qZS)-based isolated AC/AC converter as a reference. The switching strategy is also developed to achieve safe switching, which avoids current and voltage spikes without using any RC snubber. As a result, high-frequency transformer-isolated ZS (HFTI-ZS) converters retain all the benefits of their existing non-isolated counterparts, such as; wider output voltage range, reversing or maintaining phase angle, reducing harmonic and accelerating currents, and improving reliability. In addition to these benefits, HFTI in ZS AC/AC converters provides electrical isolation and safety with high power density.

Mohamed et al [49] propose a technique to analyze the behavior of high voltage transformers at high frequencies using the Hilbert Huang Transform (HHT) to eliminate the nonstationary components of partial discharge (PD) signals. This method decomposes the discharge signal into different levels and uses a least-squares technique to determine parameters such as signal gain, harmonic frequency, damping factor, and harmonic order. These parameters allow the original oscillation of the PD signal to be reconstructed. Their results are in good agreement with the measured data, indicating an efficient estimation of the PD signal propagation in the transformer windings. Pranav Raj Prakash [50] Due to their high power densities and efficiencies, high-frequency resonant converters using printed circuit board (PCB)-based transformers are gaining popularity in applications, such as datacenters and automotive. However, in such high-frequency, high-current applications, the PCB transformer's termination losses may become significant if not designed properly. This article aims to highlight multiple design considerations to minimize the termination losses while designing a PCB-based matrix transformer. Various termination techniques for full-bridge and center-tap secondary-rectifiers are studied, and it is shown that placing the devices and output filter capacitors directly on the secondary windings results in the lowest termination loss. However, this results in the output filter capacitors being split between the two secondary PCB layers, resulting in a long paralleling loop between them. It is demonstrated that the parasitic inductance of this loop undergoes parallel resonance with the filter capacitors, resulting in high circulating currents and, hence, high termination losses. Methods to mitigate this effect at the LLC converter's switching frequency are discussed. Improvements of the proposed terminations are demonstrated by modeling and measuring the transformer's ac resistance. Furthermore, the LLC converters' efficiency improvements are also showcased with the improved terminations. Both papers [49] and [50] represent advances in modeling techniques to improve transformer performance in high frequency applications.

This section describes advances in ferroelectric material characterization and measurement techniques made by several authors. Rivero Ramirez et al. [51] developed both a signal generator and a high voltage amplifier for use in a hysteresis loop characterization setup, and also implemented a data acquisition system. The result is a hardware and software system capable of analyzing ferroelectric materials, with the amplifier increasing the output signal amplitude up to 2kV. Felix et al. [52], based on the classical Preisach model - which does not consider velocity dependent hysteresis or the rate of charge motion - proposed an improvement with an additional mathematical operator to include creep phenomena. This modified Preisach model was verified by measurements using two different principles: a modified Sawyer-Tower circuit and a method based on electric current integration. Simulations performed with both methods agreed well with the ferroelectric hysteresis behavior predicted by the new model. Astudillo et al. [2] extended the ferroelectric characterization to include the analysis of the magnetoelectric coupling in the $KNbO_3 - Co$ material, using a pair of static magnetic field coils and an AC voltage source with 3kV gain. This setup also included a cooling system for thermal regulation. Their modified Sawyer-Tower circuit showed that the remanent polarization increased with temperature. At room temperature, undoped samples showed paramagnetic behavior, which changed to ferromagnetic with 5 % Co doping. The application of a magnetic field (H=1T) caused a slight but significant shift of the hysteresis loops P vs. E. A magnetostriction induced voltage shift in the sample could be responsible for this observed effect. They concluded that there is a significant magnetoelectric effect at room temperature in the KN:Co doped samples, with a calculated coupling resistance of 6.9 %.

Authors like Doru C. Lupascu et al [53] address the issue of electric field and polarization in ferroelectric samples, focusing on the influence of the dielectric interface layer and the scattered fields at the sample edges. The heterogeneity of electric fields in realistic ferroelectric samples is discussed and a detailed approach for measuring these parameters is proposed. A circuit for measuring polarization in ferroelectric samples is described. The proposed Sawyer-Tower circuit uses a current-to-voltage converter together with a lock-in amplifier to integrate the current passing through the sample, allowing the polarization to be measured accurately. The process of measuring polarization in ferroelectric samples involves converting the current generated by the polarization in the sample into a voltage signal that can be easily measured and analyzed. This is accomplished by using a current-to-voltage converter in the measurement circuit. Once the current generated by the bias in the sample is converted to a voltage signal, this signal is amplified using a lock-in amplifier. The lock-in amplifier is a device that amplifies weak signals and eliminates noise, allowing accurate measurement of the polarization in the ferroelectric sample.

On the other hand, the paper [54] deals with direct hysteresis measurements on ferroelectret films using a modified Sawyer-Tower circuit. Ferroelectret films are nonpolar polymer systems with charged internal cavities that exhibit ferroic behavior similar to that of conventional ferroelectric materials. The modified Sawyer-Tower circuit consists of a series connection of the sample, a high-voltage capacitor (C1), and a large standard capacitor (Cm). The charge flowing through the circuit is evaluated by measuring the voltage across Cm, while C1 acts as a voltage divider to protect the electrometer in the event of an electrical breakdown in the sample. The voltage applied to the sample has a waveform consisting of two positive square-wave half-cycles followed by two negative half-cycles. The authors concluded that voltage-voltage mode measurements are suitable for obtaining hysteresis curves in ferroelectret films and that the modified Sawyer-Tower circuit is a useful tool for characterizing some of their properties. They also suggested that the method could be applied to other ferroelectric materials with fast charging processes.

However, studies such as that of Nirmana Perera et al [55] provide a detailed analysis of the Sawyer-Tower method used to measure the large-signal output capacitance (Co) of power transistors. The study provides important design recommendations for obtaining accurate results in these measurements. The authors discuss the importance of understanding and measuring the output capacitance of power transistors, as this information is critical to the design and optimization of power circuits. The Sawyer-Tower method, a commonly used technique for measuring output capacitance under large-signal conditions, is described in detail. Key factors affecting the proper implementation of the Sawyer-Tower method, such as the selection of the reference capacitor (Cref), are highlighted and recommendations are given to improve the accuracy of the measurement results. In addition, simulation and experimental results are presented for different device types, including Si, SiC, and GaN, demonstrating the effectiveness and applicability of the method in a variety of device technologies. Finally, the article provides a detailed and practical insight into the measurement of power transistor output capacitance using the Sawyer-Tower circuit, highlighting its importance in the design and characterization of power devices.

In conclusion, it can be observed that in [45] there is the need to build a high voltage amplifier capable of transmitting a sinusoidal signal at a frequency of up to 20 MHz with a maximum signal of 180 Vpp, where it is compared with the conventional amplifier and it has been proved that the proposed amplifier has a lower harmonic distortion at high frequencies; it is also seen that they get a better result than the digital amplifier. On the other hand [46] proposes a source not an amplifier, whose voltage Z source has in its installation an AC/AC converter, this source-converter presents some filters that compared to what was exposed in [45] that improves its functionality, such as being able to regulate the output frequency. In its electronic topology it has input filtering, inductor, input converter cycle, high frequency transformer, output converter cycle, control switch and output filter, whose structure improves the operation of the AC/AC converter single-phase Z source developed in [47], since they differ in the design and particularly in the common ground in both the output and input signal. A family of such ZS source AC/AC converters using high frequency transformers (20kHz) with a stable and regulated output gain is visualized in [48], which, compared to the studies of [46] and [45], is more compact and presents a better performance on current and voltage peaks without using any RC snubber. Pranav Raj Prakash [50] and [49] study the dynamic behavior of transformers, and [49] presents an inductive and capacitive coupling model of a two-winding transformer that favors the gain as a function of frequencies up to MHz. Other articles such as [40], [41] and [43] propose instrumental architectures (hardware-software) where the coupling of electronic systems limit the ferroelectric measurements in front of periodic signals of different harmonic content and frequency up to MHz, with limitations such as maintaining a high AC voltage regulated in gain at high and low frequencies, connectivity with other devices or industrial type electronic equipment, preservation of the waveform that stimulates the material, etc... Obviously, it is necessary to generate electronic prototypes with these characteristics, which allow to evaluate the samples (ferroelectric materials) to different harmonic contents and frequencies, in addition to providing the functionalities to operate at high and low frequencies.

4 Conclusions

The study of the electrical charge storage of $BaTiO_3$ is fundamental to understand its ferroelectric properties and its behavior as a function of harmonic content and frequency. Through this literature review, the importance of analyzing the electrical polarization response of this material under different conditions is demonstrated, which allows advancing the knowledge of its ferroelectric properties. The relevance of the methods and techniques developed for the characterization of $BaTiO_3$ is highlighted, as well as the adaptation of sources and amplifiers for ferroelectric analysis, which broadens the possibilities of study and optimizes the measurement of its properties. The taxonomy used in the study provides a detailed structure to study the specific properties of $BaTiO_3$ in terms of electrical polarization response versus harmonic content and frequency, as well as the adaptation of measurement equipment. The established selection criteria allowed the identification of 60 relevant primary studies that specifically address key aspects of the electrical behavior of this material. Overall, the research not only contributes to the advancement of the knowledge of $BaTiO_3$ in the field of ferroelectricity, but also opens new opportunities for studies that can improve the understanding of the ferroelectric properties of this ceramic material and new ones.

The systematic review of the literature highlights the importance of promoting new studies in the field of ferroelectric properties of $BaTiO_3$. By analyzing the electrical polarization response of this material as a function of harmonic content and frequency, it is evident that there is a need to deepen the knowledge of its ferroelectric behavior and the potential applications that can be derived from this knowledge. The variety of academic databases consulted and the number of relevant studies identified demonstrate the interest and importance of this topic in the scientific community. The taxonomy used in the research provides a clear guide to address the key aspects of the study of the ferroelectric properties of $BaTiO_3$, facilitating the identification and analysis of the specialized literature in this field. Therefore, the literature review not only consolidates the state of the art in the study of $BaTiO_3$, but also lays the foundation for future research that can broaden our understanding of this material and its applications in various fields of engineering and materials science.

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