HYSTERESIS CHARACTERISTICS ANALYSIS FOR FERROELECTRIC TFTS AND IT'S APPLICATION TO DRAM.

by

SHAH MD. ASHIK MAHMUD(190021224)

SHADID ISLAM (190021134)

SHAFAIET NEWAZ WORNOB (190021237)

MD.KHAIRUL BASHER(190021328)

The Thesis will be Submitted to the Faculty for Fulfillment of the Requirement for the Degree of

BACHELOR OF SCIENCE IN
ELECTRICAL & ELECTRONIC ENGINEERING

Department of Electrical and Electronic Engineering
Islamic University of Technology (IUT)
Gazipur, Bangladesh

JUNE 2024

HYSTERESIS CHARACTERISTICS ANALYSIS FOR FERROELECTRIC TFTS AND IT'S APPLICATION TO DRAM.

Approved by:

26.6.24

Dr. Mohammad Masum Billah

Supervisor and Assistant Professor,
Department of Electrical and Electronic Engineering,
Islamic University of Technology (IUT),
Boardbazar, Gazipur-1704.

Date: ……

Table of Contents

Declaration of Authorship

We, declare that the thesis titled," HYSTERESIS CHARACTERISTICS ANALYSIS FOR FERROELECTRIC TFTS AND IT'S APPLICATION TO DRAM.and the works presented in it are our own.

We ensure that this study is completed within the scope of the requirements for the Bachelor of Science degree in Electrical and Electronics Engineering at the Islamic University of Tech nology (IUT). This thesis or any portion thereof has not been submitted for any other degree or certificate.We have always clearly attributed the sources when we have consulted the published work of others

Submitted by:

Shah Md. Ashik Mahmud

Student ID: 190021224

Shadid Islam

Student ID: 190021134

Shafaiet Newaz Wornob

Student ID: 190021237

Md. Khairul Bashar

Student ID: 190021328

Acknowledgments

First of all, we would like to express our gratitude to Almighty Allah (cc), the possessor of mercy and compassion, who gave us the strength and patience to complete this article.

Our thesis advisor Dr. Mohammad Masum Billah from the Department of Electrical and Electronic Engineering, Islamic University of Technology (IUT). His valuable guidance, unw avering support and suggestions were crucial in our research. His wisdom and guidance have been an inspiration throughout this journey, and we thank him for his continued support and encouragement.

Also All the faculty Of IUT for their constant support And inspiration
Their knowledge, skills and motivation play an important role in our education and research.

Finally, we would like to thank our family for their support, understanding and support during the writing of this article. Their love, patience and belief in our abilities motivated us t o move forward.

List of Tables

List of Figures

List of Acronyms

FE - Ferroelectric

P - Polarization

E - Electric Field

RH - Remanent Hysteresis

PL - Polarization Loop

CH - Coercive Hysteresis

CHL - Coercive Hysteresis Loop

RHV - Remanent Hysteresis Voltage

RHM - Remanent Hysteresis Moment

SH - Saturation Hysteresis

SHL - Saturation Hysteresis Loop

C - Curie Temperature

HLP - Hysteresis Loop Parameters

HED - Hysteresis Energy Density

Abstract

This thesis presents a brief analysis of the hysteresis characteristics of various ferroelectric materials. Ferroelectric materials shows spontaneous remanent polarization that can be modified by an external field. This property is crucial for applications in non-volatile memories, actuators, and sensors. By examining hysteresis loops, the study aims to understand the distinct behavior of ferroelectric materials under different electric fields and their impact on practical applications. Experimental and theoretical approaches are used to elucidate the mechanisms driving hysteresis in ferroelectrics, providing insights into optimizing material performance for specific applications.

Chapter 1: Introduction

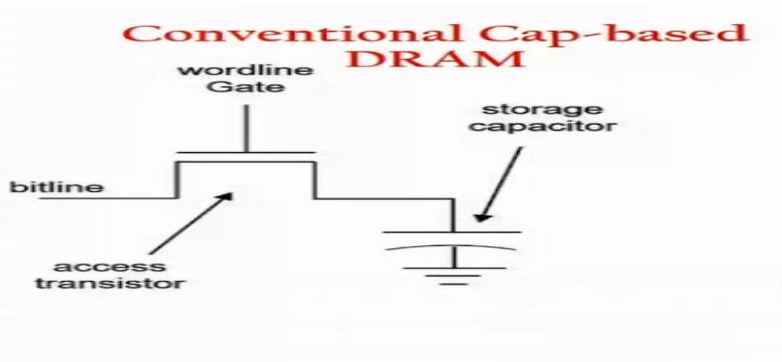
1.1 Background & Motivation

Thin Film Transistor is used for DRAM in semiconductor industry,however we are trying to design it using ferroelectric material,and we will analyze the hysteresis characteristics of ferroelectric material for better switching speed of the memory,while we will use only transistor instead of capacitor since capacitor is bulky for fabrication.

Ferroelectric materials have potential applications beyond traditional memory devices, including neuromorphic computing, non-volatile logic, and energy harvesting. Investigating ferroelectric materials in DRAM can uncover new opportunities for leveraging these materials in emerging technologies and applications.

Research on ferroelectric materials in DRAM can lead to the exploration of novel device architectures and memory cell designs. By leveraging the unique properties of ferroelectric materials, researchers can develop innovative memory solutions with enhanced functionalities, such as multi-bit storage and analog computing capabilities.

Figure 1.1.1



[3]

Figure 1.1.2

[3]

1.2 Objectives

The main objectives of the thesis are:

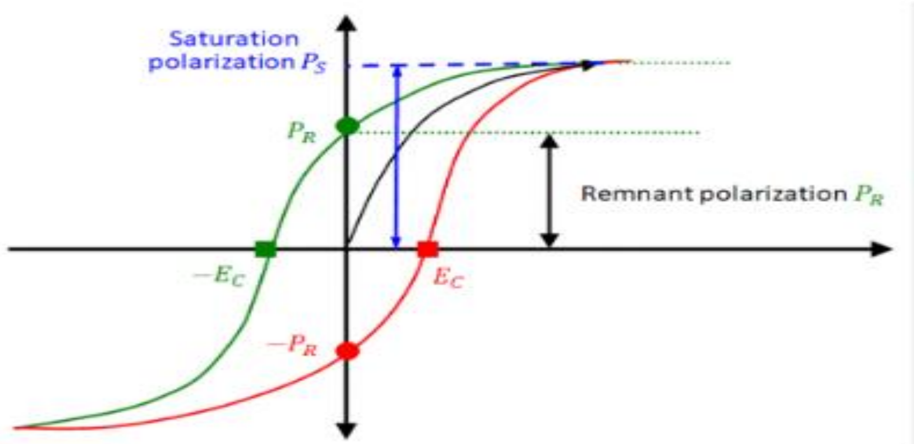
To analyze the hysteresis characteristics of different ferroelectric materials.

To understand the factors influencing hysteresis behavior.

To compare experimental results with theoretical models.

To propose optimization strategies for material performance in practical applications.

Figure 1.1.2



[11]

1.3 Scope of the Study

This analysis shows the hysteresis properties of various ferroelectric materials, incorporating experimental measurements, theoretical modeling, and application-oriented analysis. The focus is on understanding the intrinsic and extrinsic factors affecting hysteresis loops and their implications for real-world applications.

The reason why we use ferroelectric material for design

1. Good Speed.
2. Low Power Consumption.
3. Scalability.
4. Piezoelectric Properties.
5. Tunable Properties.
6. High Endurance

1.4 Structure of the Thesis

The thesis is maintained as like: Chapter 2 shows existing figure on ferroelectricity and hysteresis. Chapter 3 provides the theoretical framework for understanding hysteresis in ferroelectric materials. Chapter 4 outlines the materials and methods used in analysis. Chapter 5 presents the experimental results, followed by a discussion in Chapter 6. Chapter 7 focuses on the optimization and applications of ferroelectric materials based on their hysteresis characteristics. Finally, Chapter 8 finishes the study with a summary of solution and future outcomes

Chapter 2: Literature Review

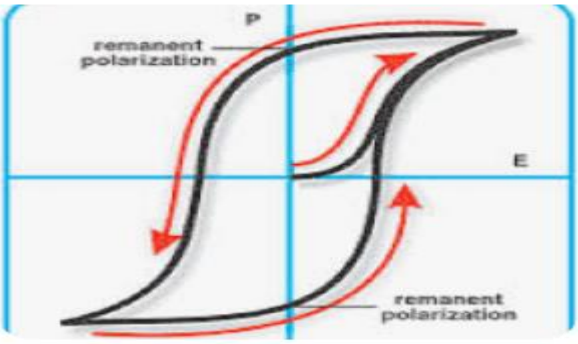
2.1 Ferroelectricity: Fundamentals

Ferroelectricity refers to materials that exhibit electrical polarization that can be reversed by the application of electricity. This phenomenon is similar to piezoelectricity, but is uni que in its ability to control polarization in the absence of an external source. Ferroelectric materials are essentially perovskite oxides; Barium titanate (BTO) and lead zirconate titan ate (PZT) are important examples. With electric field E and polarization P:

$D=\epsilon 0E+P$ [1] [3]

where $\epsilon 0$ is the permittivity . In ferroelectric materials, the polarization P can be varied between different states by applying an external field.

Figure 2.1.1



[1]

2.2 Historical Development

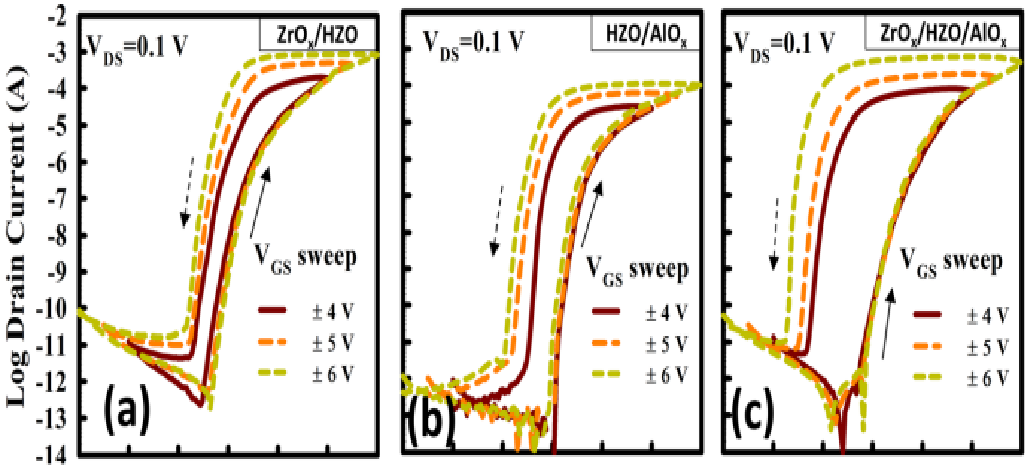
The analysis of ferroelectric materials shows to the early 20th century. The invention of ferroelectricity in Rochelle salt by Valasek and the subsequent development of materials like PZT and BTO marked significant milestones. Advances in synthesis techniques, such as sol-gel processing and molecular beam epitaxy, have created the high-quality ferroelectric TFTs, which are crucial for modern applications.

2.3 Hysteresis in Ferroelectric Materials

Hysteresis curves in different ferroelectric materials measures the lag between the applied electric force & field and the applied remanent polarization. The hysteresis loop can be described by the relation:

P=Pstanh(Ec/E)[7]

Figure 2.3.1

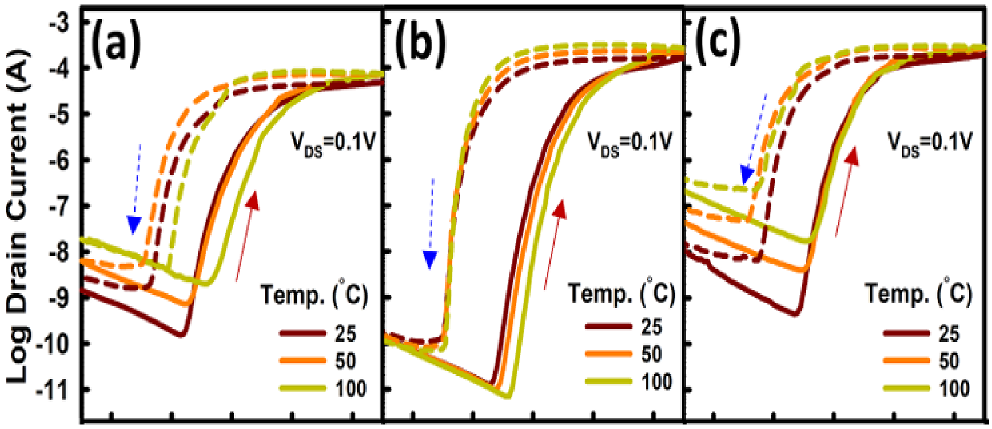


[12]

2.4 Previous Studies on Hysteresis Analysis

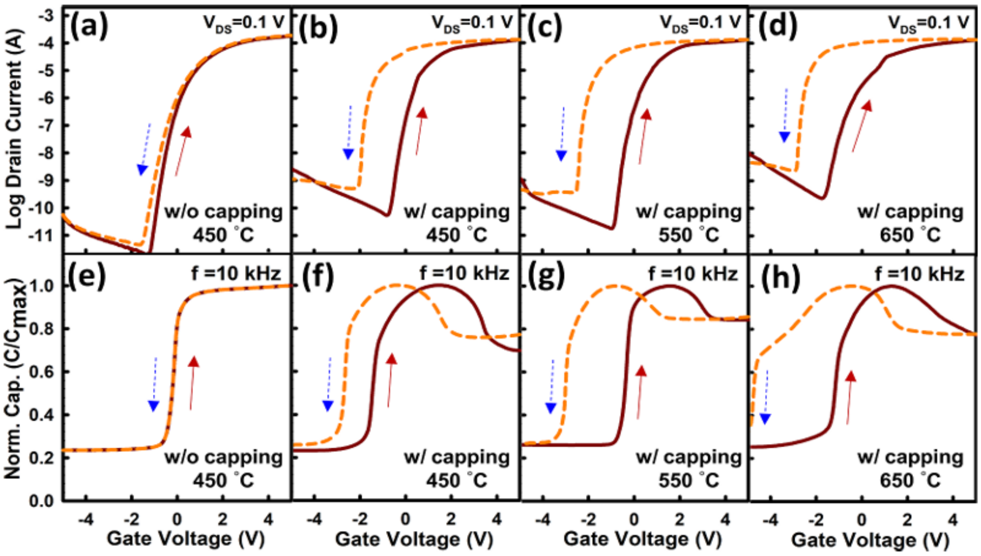
Extensive research has been conducted on that characteristics of ferroelectric materials. Studies have explored impact of temperature, frequency, and external stress on hysteresis behavior. For instance, Tagantsev et al. investigated the frequency dependence of hysteresis in ferroelectric ceramics, while Haertling examined the temperature effects on PZT films. These studies provide a foundation for understanding the factors influencing hysteresis and guiding the development of ferroelectric devices.

Figure 2.4.1



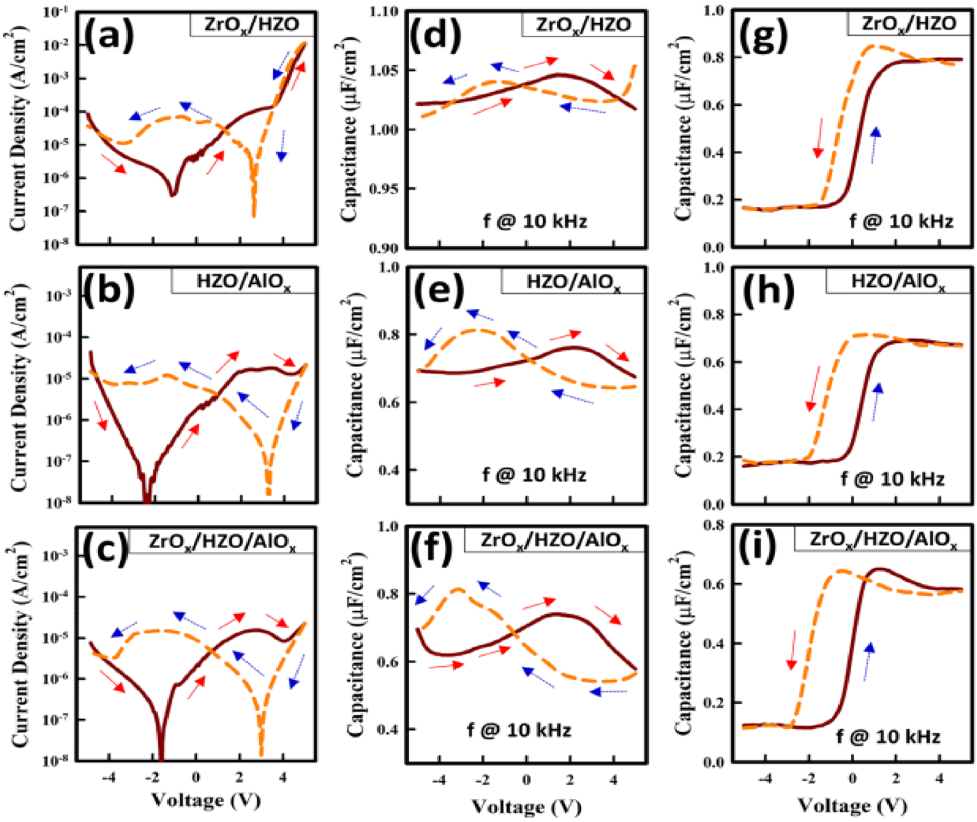
[8][1][2]

Figure 2.4.2



[10][1][2]

Figure 2.4.3



[9][1][2]

Chapter 3: Theoretical Framework

3.1 Ferroelectric Transistors,Domains & Polarization

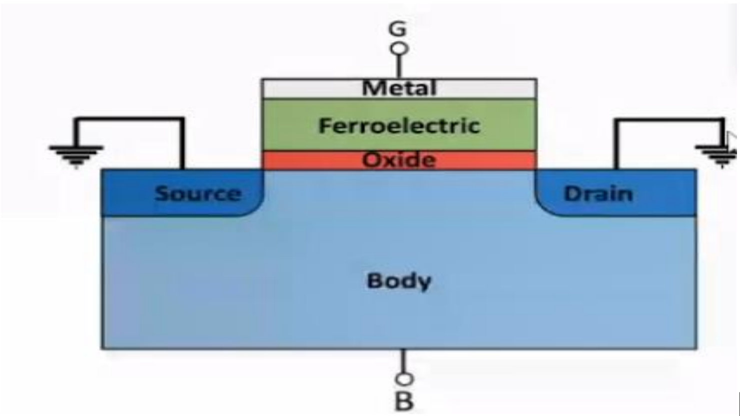
Ferroelectric materials consist of regions called domains, each with a uniform polarization direction. The behavior of these domains under an electric field influences the overall hysteresis characteristics. Domain wall characteristics, the boundaries between the domains with different type of polarization directions, play a vital role in polarization switching.

The domain structure may be explained by the Landau-Ginzburg-Devonshire (LGD) theory,

The equilibrium polarization can be found by minimizing this free energy.

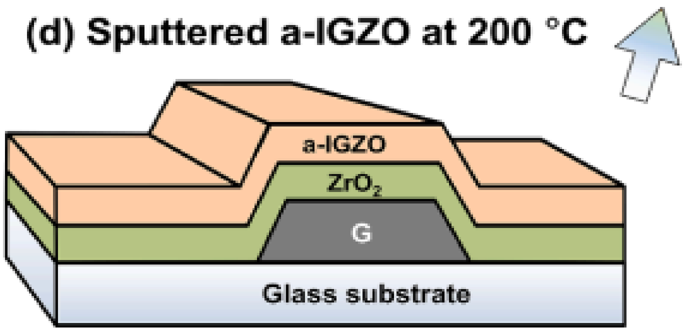
F=αP2+βP4+γP6−EP **[5]**

Figure 3.1.1



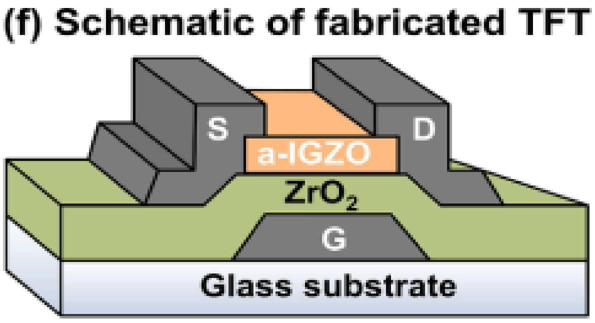
[13][11][12]

Figure 3.1.2



[10][1][13]

Figure 3.1.3



[11][1][2]

3.2 Hysteresis Loop Characteristics

The hysteresis shows the relationship between applied electric field (E) and remanent polarization (P) in ferroelectric materials. Key parameters include:

- **Coercive Field (Ec)**: The field need to switch the polarization direction.
- **Remanent Polarization (Pr)**: The residual polarization after the field is removed.
- **Loop Area**: Related to energy dissipation during the polarization cycle.

The area of the hysteresis loop is given by:

$A=\oint P\, dE$**[6]**

Normal Mosfet equation give output like PN junction like figure that’s why we have to control off current and have to modify the off current equation.like figure below

Figure 3.2.1

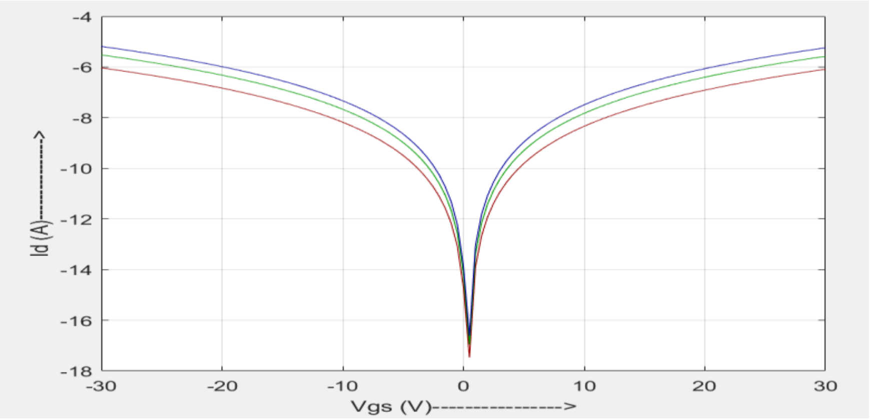
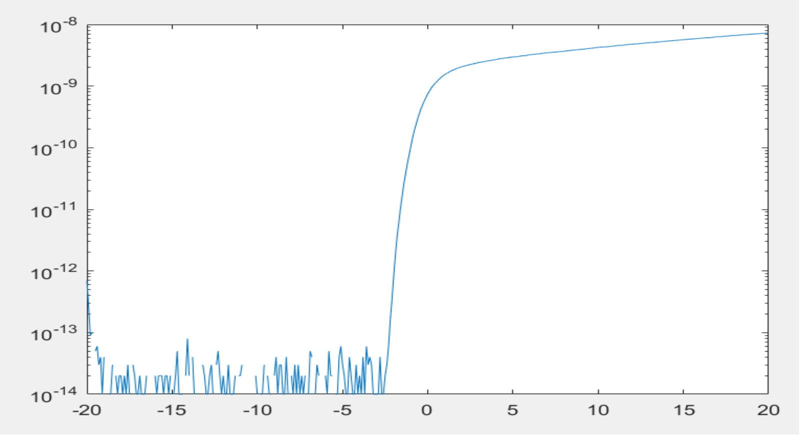


Figure 3.2.2



3.3 Factors Influencing Hysteresis

The factors influence the hysteresis curves of ferroelectric materials:

Material Composition: Type of ferroelectric material affects domain structure and switching dynamics.

Temperature: Higher temperatures can reduce the coercive field and increase remanent polarization.

Electric Field Amplitude and Frequency: Varying these parameters affects the shape and area of the hysteresis loop.

External Stress: Applied mechanical stress can influence domain motion and polarization. The effect of temperature on the coercive field

Interface trap density significantly affects the performance of memory devices.

- Charge Trapping:
- Threshold Voltage Shift:
- Data Retention:
- Cycling Endurance:
- Polarization Stability:
- Speed and Power Consumption:

Interface trap density

- Threshold Voltage Shift
- Subthreshold swing
- Carrier Mobility
- General Equation

$$\Delta V_{th} = \frac{q \cdot D_{it}}{C_{ox}}$$ **[8]**

$$S = \ln(10) \cdot \frac{kT}{q} \left(1 + \frac{q \cdot D_{it}}{C_{ox}}\right)$$ **[7]**

$$I_D \approx \frac{\mu \cdot C_{ox} \cdot (V_{GS} - V_{th}) \cdot V_{DS}}{L}$$ **[8]**

$$I = I_0 \cdot (1 - \beta \cdot D_{it}) \cdot e^{-\gamma \cdot D_{it}}$$ **[2]**

3.4 Models of Hysteresis in Ferroelectric Materials

Theoretical models provide frameworks for understanding hysteresis behavior:

Landau-Ginzburg-Devonshire (LGD) Theory: Analysis the energy of a ferroelectric system as a function of polarization and temperature.

Preisach Model: Represents hysteresis as a superposition of the hysteresis operators. The Preisach model describes polarization

$\rho(\alpha,\beta)$ is the distribution function of the hysteresis operators characterized by thresholds

Domain Wall Models: Focus on the movement of domain walls under an applied electric field, influencing hysteresis characteristics.

Chapter 4: Materials and Methods

4.1 Selection of Ferroelectric Materials

The study investigates several ferroelectric materials, including:

Barium Titanate (BTO): Better known for its good dielectric constant and widespread use in capacitors.

Lead Zirconate Titanate (PZT): A widely studied ferrelectric material with applications in sensors and actuators due to its strong piezoelectric properties.

Potassium Niobate (KNbO3): Exhibits interesting ferroelectric properties and is used in electro-optic applications.

4.2 Stimulation Setup

The Stimulation setup includes:

Ferroelectric Tester: Equipped with a high-voltage amplifier and a lock-in amplifier for precise hysteresis measurements.

Sample Preparation: Thin films and bulk samples are prepared with electrodes to facilitate the application of electric fields.

4.3 Measurement Techniques

Hysteresis measurements involve:

P-E Loop Tracing: Recording the remanent polarization response to a cyclic applied electric field. The applied field EEE is varied sinusoidally as:

Pulsed Polarization Measurements: Capturing transient polarization changes.

4.4 Data Analysis Procedures

Statistical analysis is used to evaluate the impact of variables such as temperature and frequency on hysteresis behavior.

Data analysis focuses on extracting key parameters from the hysteresis loops:

- **Coercive Field** : Determined from the field at which polarization switches.
- **Remanent Polarization** : Measured after removing the electric field.
- **Loop Area**: Calculated to assess energy dissipation. The energy dissipation per cycle

The following table should be considered for data analysis

Table 4 .4.1

Applied Electric Field (E)	Polarization (P)	Hysteresis Loop
Negative High	Negative	Retentivity
Negative Low	Negative	
Zero	Zero	
Positive Low	Positive	
Positive High	Positive	Saturation

[12]

Table 4 .4.2

Ferroelectric Material	Hysteresis Loop Shape	Coercive Field	Remanent Polarization	Saturation Polarization	Curie Temperature
Lead Zirconate Titanate (PZT)	Rounded	High	High	High	~360°C
Barium Titanate (BaTiO3)	Squared	Moderate	Moderate	High	~120°C
Potassium Niobate (KNbO3)	Asymmetric	Low	Moderate	Moderate	~420°C
Lithium Niobate (LiNbO3)	Elliptical	Moderate	Moderate	Moderate	~1250°C
Bismuth Ferrite (BiFeO3)	Asymmetric	Moderate	High	High	~830°C

[10]

Chapter 5: Stimulation Results

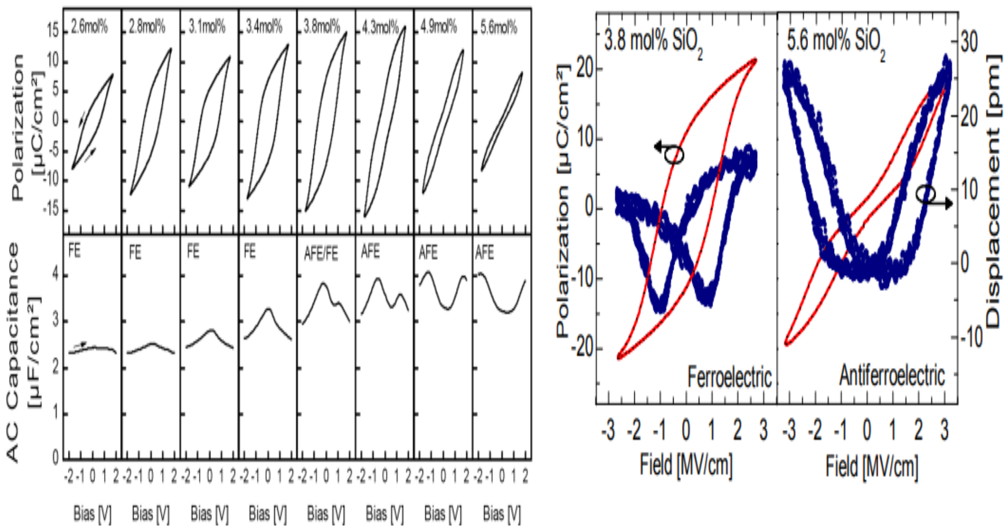
5.1 Hysteresis Loop Observations

The hysteresis loops of the selected ferroelectric materials exhibit distinct characteristics:

Barium Titanate (BTO): Shows well-defined hysteresis loops with moderate coercive fields and high remanent polarization. The relationship can be approximated by:

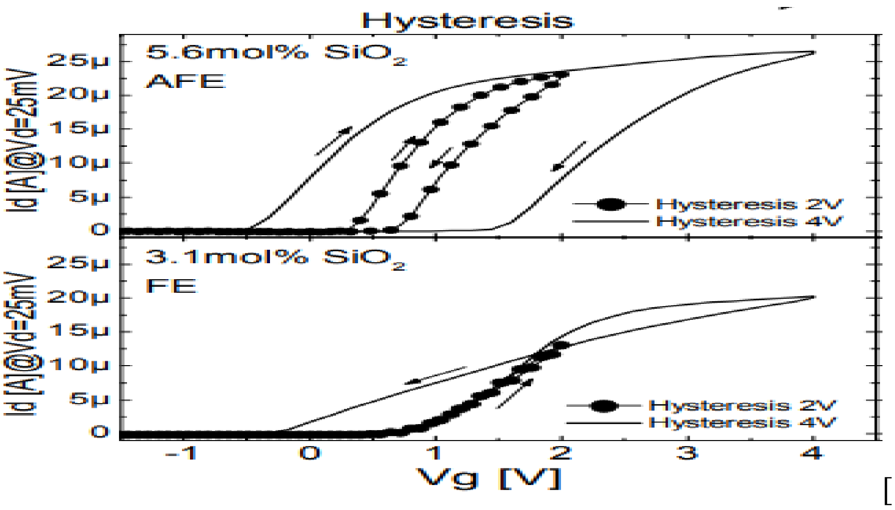
Lead Zirconate Titanate (PZT): Exhibits sharp switching behavior and large remanent polarization, for making it applicable for memory device applications.

Figure 5.1.1



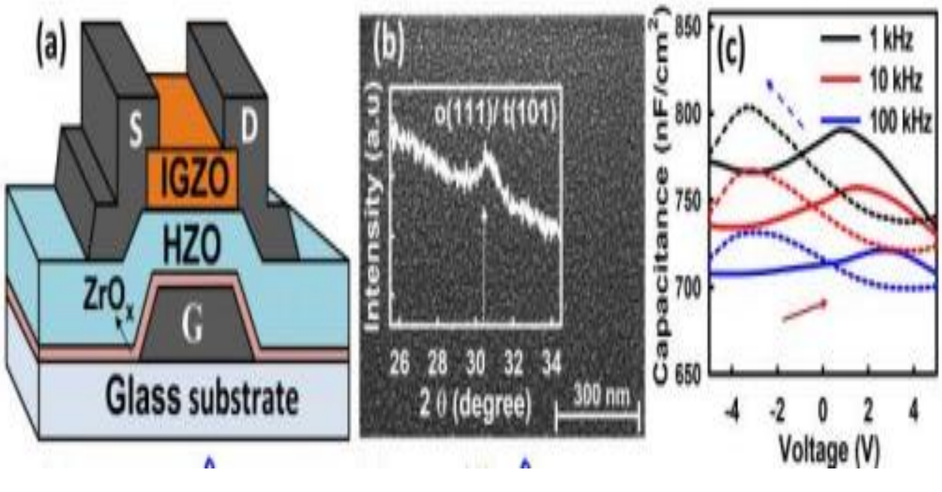
[7][10]

Figure 5.1.2



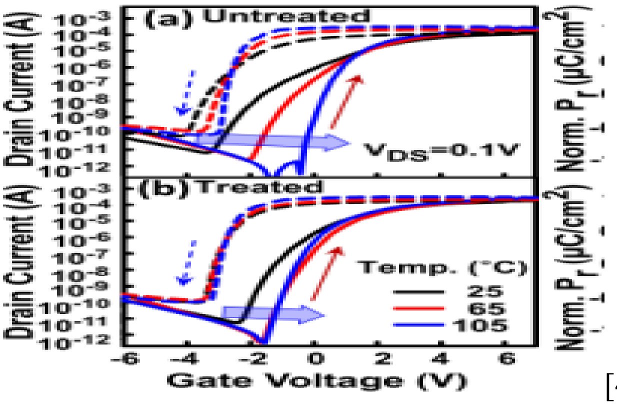
[12][10]

Figure 5.1.3



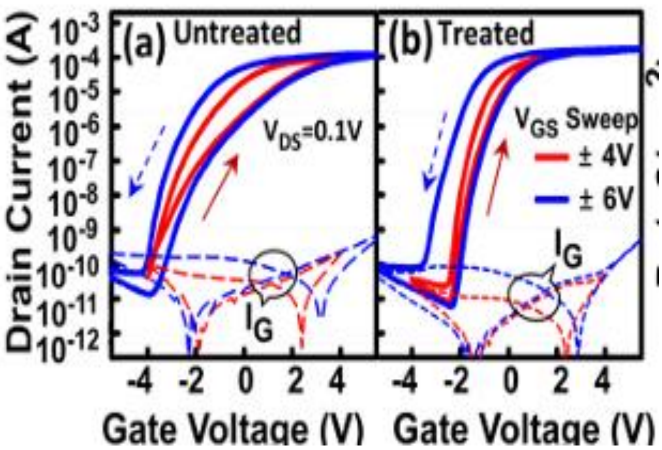
[8][10]

Figure 5.1.4



[4][1]

Figure 5.1.5

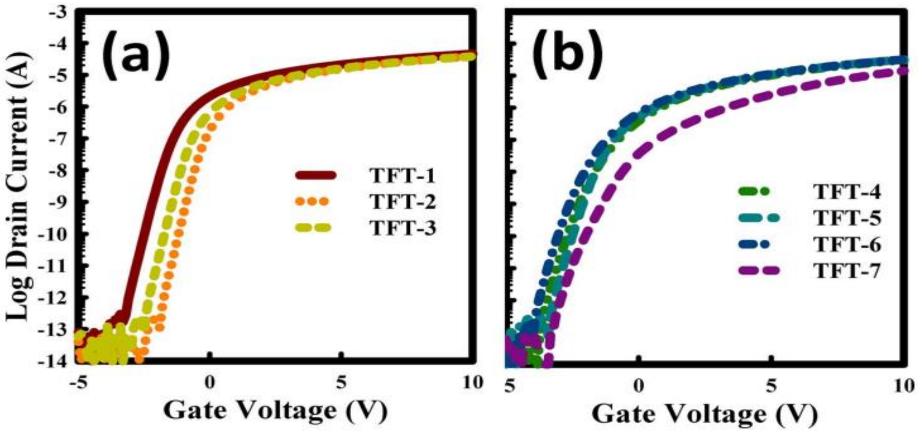


[6][1]

5.2 Comparative Analysis of Different Materials

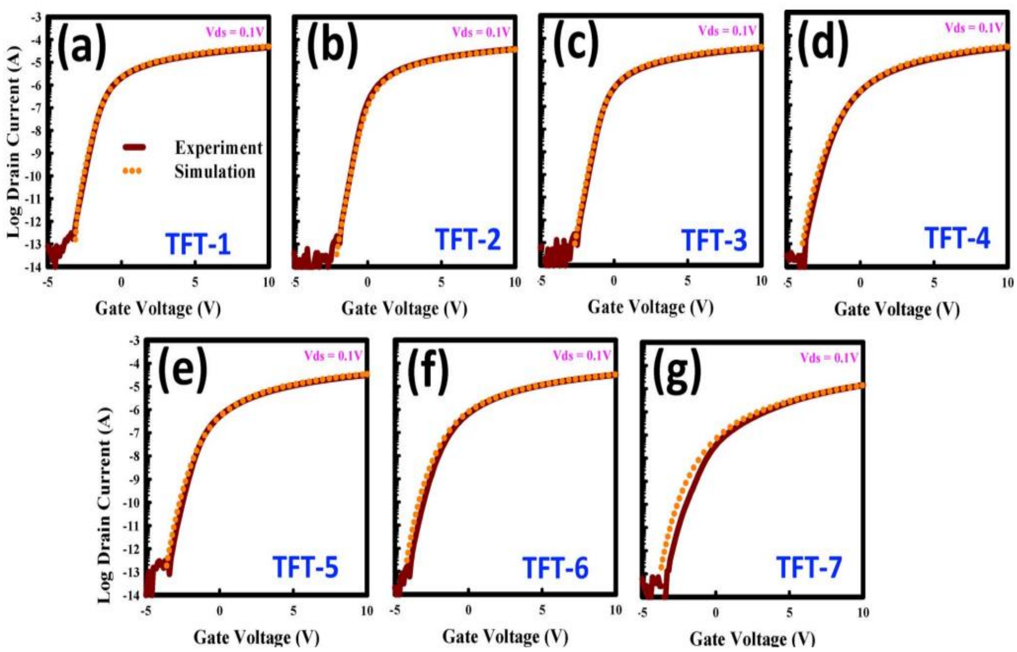
Comparative analysis reveals differences in hysteresis behavior among the materials:

Figure 5.2.1



[1]

Figure 5.2.2



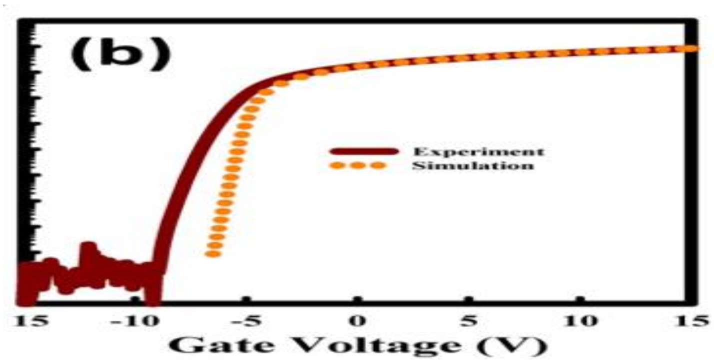
[2]

5.3 Temperature and Frequency Dependence

Temperature and frequency significantly affect hysteresis behavior:

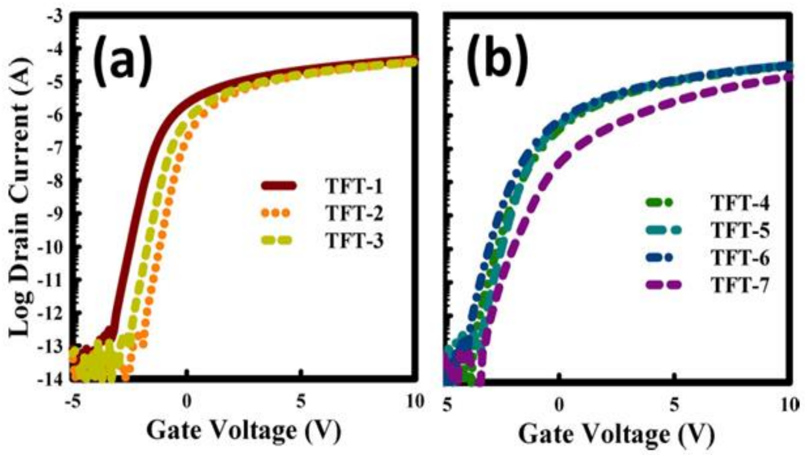
Temperature: Higher temperatures generally reduce the applied coercive field and increase polarization. The temperature dependence can be modeled as:

Figure 5.3.1



[13]

Figure 5.3.2



[11]

5.4 Stimulation Of Memory Window

First we stimulate the hysteresis curve for different ferroelectric materials in figure 5.4.1 then we did post fabrication annealing for reduce trap density in figure 5.4.2 ,then we again stimulate by using different dielectric materials at 5.4.3 and observe the results and the last two figures we stimulate the hystertesis curve by varying material properties and trap density factors

Figure 5.4.1

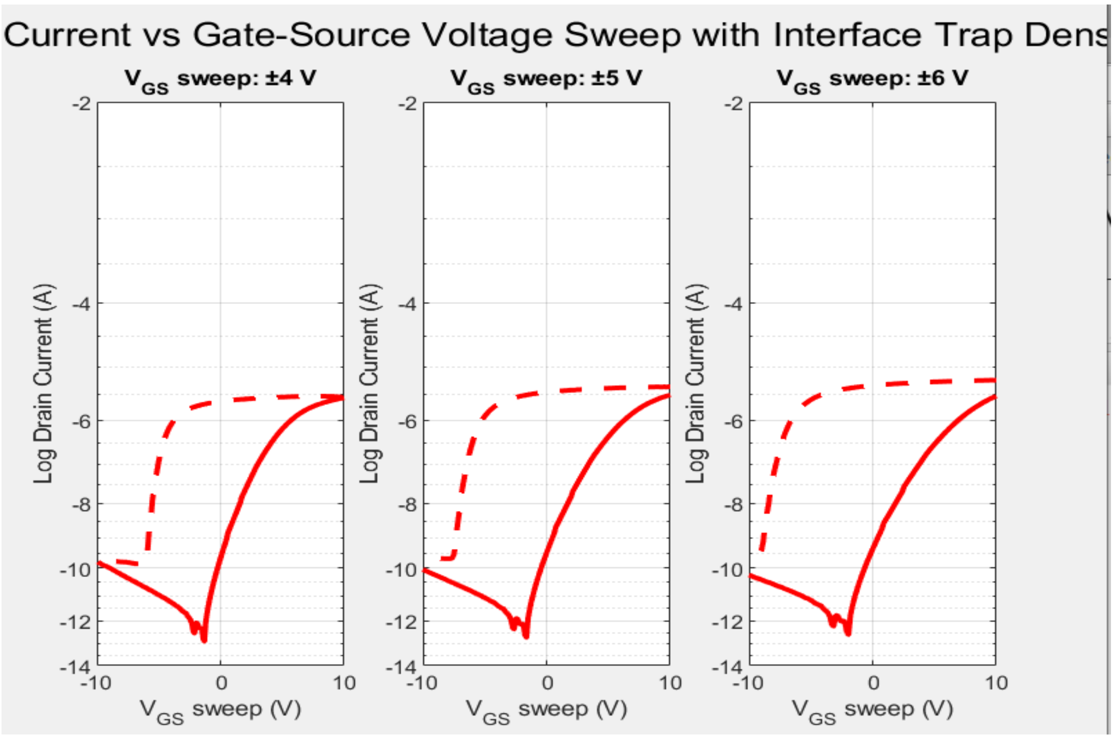


Figure 5.4.2

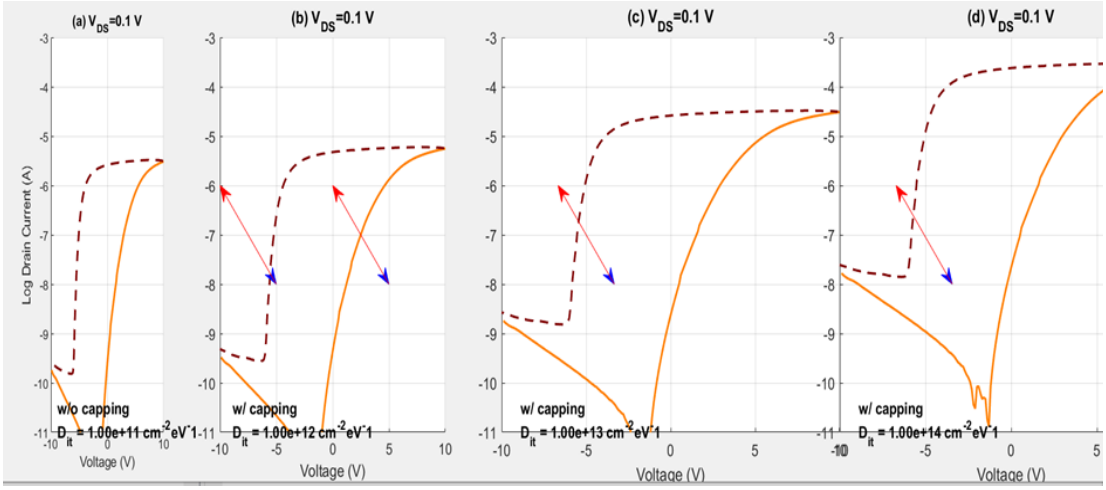


Figure 5.4.3

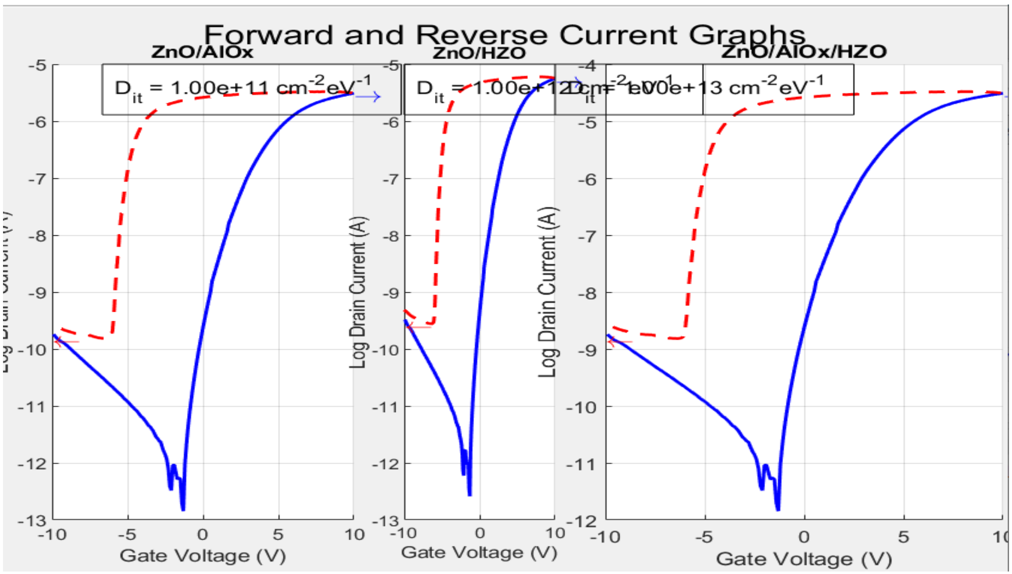
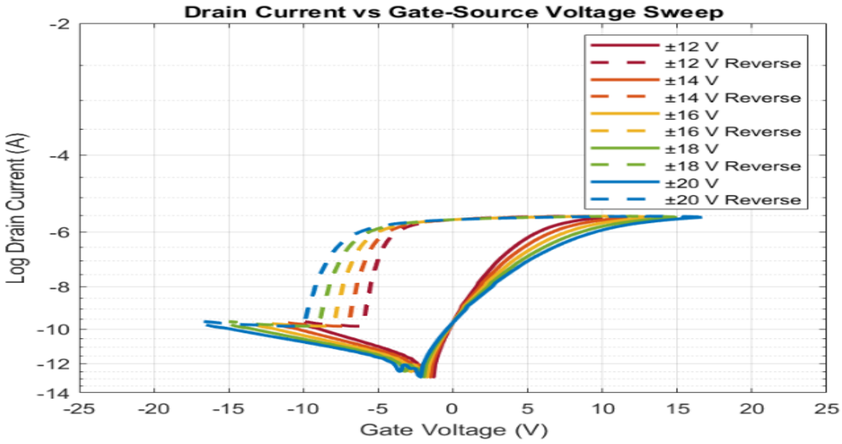
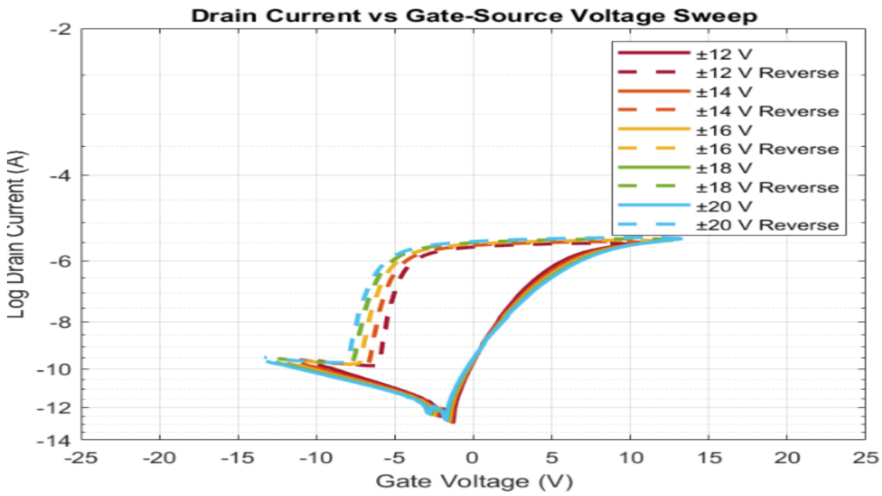


Figure 5.4.4



- Material Properties=analysis remanent polarization (Pr) and coercive field (Ec) [10]

Figure 5.4.5



Trap density factors we considered

- k = Boltzmann constant (J/K) ,won’t change
- T = Temperature (K) will change
- q = Electron charge (C) won’t change
- C_ox = Oxide capacitance per unit area (F/cm^2) will change

Chapter 6: Discussion

6.1 Interpretation of Hysteresis Characteristics

The stimulation results provide insights into the hysteresis behavior of ferroelectric materials:
Domain Switching Dynamics: Observations align with theoretical models of domain wall motion and polarization reversal. The switching dynamics can be described by:
Material-Specific Behavior: Variations in coercive field and remanent polarization are linked to intrinsic material properties and domain structures.
We have to reduce trap density as much as possible for finding the best possible electrical characteristics in Mos device.
More less hysteresis area will give less trap density,will enhance the device performance.

6.2 Comparison with Theoretical Models

Comparison with theoretical models highlights:

LGD Theory: Provides a good fit for the temperature dependence of hysteresis behavior. The free energy
Preisach Model: Useful for understanding the frequency dependence and loop shape variations. The polarization
Domain Wall Models: Explain the impact of external stress on hysteresis characteristics. The domain wall velocity

6.3 Implications for Applications

The hysteresis characteristics have significant implications for practical applications:

Memory Devices: Materials with high remanent polarization and sharp switching (e.g., PZT) are ideal for non-volatile memories.
Sensors and Actuators: Materials with moderate coercive fields and stable loops (e.g., BTO) are suitable for sensors and actuators.

Electro-Optic Applications: Materials like KNbO3 with unique hysteresis characteristics can be used in electro-optic devices.

Future Scopes:

- **Energy-efficient memory devices**: Improved performance in non-volatile memory applications.
- **Advanced logic devices**: Integration into CMOS technology for enhanced computing power.
- **Sensor applications**: Development of high-sensitivity sensors for various applications.
- **Piezoelectric devices**: Enhanced piezoelectric properties for actuators and sensors.
- **Energy harvesting**: Utilization in energy harvesting devices for sustainable technology.
- **Flexible electronics**: Integration into flexible and wearable electronic devices.
- **Tunable capacitors**: Applications in tunable capacitors for RF and microwave technologies.
- **Quantum computing**: Potential use in quantum computing components for advanced processing capabilities.
- **Photovoltaic applications**: Improved efficiency in photovoltaic cells for solar energy conversion.
- **Data storage solutions**: Increased storage capacities in next-generation data storage technologies.

6.4 Limitations of the Study

The study has some limitations:

Sample Preparation Variability: Differences in sample preparation can affect hysteresis measurements.

External Factors: Environmental factors like humidity and mechanical stress may influence hysteresis behavior.

Model Limitations: Theoretical models may not fully capture the complexity of domain dynamics and material-specific effects.

Chapter 7: Optimization and Applications

7.1 Optimizing Ferroelectric Performance

Optimizing the performance of ferroelectric materials involves:

Material Composition: Tailoring the composition to achieve desired hysteresis characteristics.

Domain Engineering: Controlling domain structures to enhance switching behavior and stability.

Processing Techniques: Using advanced techniques like epitaxy and doping to improve material quality.

For Best Outputs:

- Introduce different type of ferroelectric material for designing.
- Find the ferroelectric materials consist of best possible material properties.
- Mitigate interface trap density effect.
- Post-fabrication annealing techniques.
- Instead of memory try to implement other devices.

7.2 Application-Specific Material Selection

Material selection for specific applications should consider:

Memory Devices: Prioritize materials with high remanent polarization and fast switching.

Sensors and Actuators: Focus on materials with moderate coercive fields and stable hysteresis loops.

Electro-Optic Devices: Choose materials with unique hysteresis characteristics that enhance electro-optic performance.

7.3 Case Studies in Memory Devices and Sensors

Case studies highlight the practical applications of ferroelectric materials:

Non-Volatile Memories: PZT is widely used in ferroelectric (FeRAM) for its high remanent polarization and sharp switching.

Sensors: BTO is commonly used in sensors for its high dielectric constant and stable hysteresis behavior.

Electro-Optic Modulators: $KNbO_3$ is used in electro-optic modulators due to its distinctive hysteresis characteristics.

Chapter 8: Conclusion

8.1 Summary of Results

The stimulation provides a comprehensive analysis of the hysteresis characteristics of various ferroelectric materials:

Distinct Behavior: Each material exhibits unique hysteresis characteristics influenced by composition, temperature, frequency, and external stress.

Theoretical Models: Experimental results are compared with theoretical models to understand the underlying mechanisms of hysteresis.

Application Implications: The findings have significant implications for optimizing ferroelectric materials for specific applications.

8.2 Contributions to the Scintific Field

This thesis contributes to the science by:

Giving detailed Analysis: Offering a detailed analysis of hysteresis characteristics for various ferroelectric materials.

Enhancing Understanding: Enhancing the understanding of factors influencing hysteresis behavior.

Guiding Optimization: Providing insights into optimizing material performance for practical applications.

8.3 Future Research Directions

Future research should focus on:

Advanced Characterization Techniques: Employing advanced techniques to study domain dynamics and hysteresis behavior.

New Ferroelectric Materials: Exploring new ferroelectric materials with improved hysteresis characteristics.Integration into Devices: Investigating the integration of optimized ferroelectric materials into advanced electronic device

Chapter 9

Demonstration of Outcome Based Education (OBE)

9.1Introduction

Outcomes-Based Education (OBE) is an educational approach that focuses on defining specific learning outcomes or objectives that we are expected to achieve by the end of a course or program. In the context of research, OBE emphasizes the importance of integrating research skills, competencies, and outcomes into the educational experience to prepare us for success in conducting scholarly inquiry and contributing to our field of study.

9.2Course Outcomes (COs) Addressed

The following table shows the COs addressed in EEE 4700 for Project and Thesis.

COs	CO Statement	POs	Put Tick (√)
			EEE 4700
CO1	Identify a contemporary real life problem related to electrical and electronic engineering by reviewing and analyzing existing research works.	PO2	√
CO2	Determine functional requirements of the problem considering feasibility and efficiency through analysis and synthesis of information.	PO4	√
CO3	Select a suitable solution and determine its method considering professional ethics, codes and standards.	PO8	√
CO4	Adopt modern engineering resources and tools for the solution of the problem.	PO5	√
CO5	Prepare management plan and budgetary implications for the solution of the problem.	PO11	√
CO6	Analyze the impact of the proposed solution on health, safety, culture and society.	PO6	√
CO7	Analyze the impact of the proposed solution on environment and sustainability.	PO7	√
CO8	Develop a viable solution considering health, safety, cultural, societal and environmental aspects.	PO3	
CO9	Work effectively as an individual and as a team member for the accomplishment of the solution.	PO9	√

CO10	Prepare various technical reports, design documentation, and deliver effective presentations for demonstration of the solution.	PO10	√
CO11	Recognize the need for continuing education and participation in professional societies and meetings.	PO12	

9.3Aspects of Program Outcomes (POs) Addressed

The following table shows the aspects addressed for certain Program Outcomes (POs) addressed in EEE 4700 for Project and Thesis.

	Statement	Different Aspects	Put Tick (√)
PO2	**Problem analysis:** Identify, formulate, research literature and analyse complex electrical and electronic engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences and engineering sciences.		√
PO4	**Investigation:** Conduct investigations of complex electrical and electronic engineering problems using research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of information to provide valid conclusions.	Design of experiments	√
		Analysis and interpretation of data	√
		Synthesis of information	√
PO6	**The engineer and society:** Apply reasoning informed by contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to professional engineering practice and solutions to complex electrical and electronic engineering problems.	Societal	√
		Health	
		Safety	√
		Legal	√
		Cultural	
PO7	**Environment and sustainability:** Understand and evaluate the sustainability and impact of professional engineering work in the solution of complex electrical and electronic engineering problems in societal and environmental contexts.	Societal	√
		Environmental	
PO8	**Ethics:** Apply ethical principles embedded with religious values, professional ethics and responsibilities, and norms of electrical and electronic engineering practice.	Religious values	
		Professional ethics and responsibilities	√
		Norms	√

PO9	**Individual work and teamwork:** Function effectively as an individual, and as a member or leader in diverse teams and in multi-disciplinary settings.	Diverse teams	√
		Multi-disciplinary settings	√
PO10	**Communication:** Communicate effectively on complex engineering activities with the engineering community and with society at large, such as being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions.	Comprehend and write effective reports	√
		Design documentation	√
		Make effective presentations	√
		Give and receive clear instructions	√
PO11	**Project management and finance:** Demonstrate knowledge and understanding of engineering management principles and economic decision-making and apply these to one's own work, as a member and leader in a team, to manage projects and in multidisciplinary environments.	Engineering management principles	√
		Economic decision-making	√
		Manage projects	√
		Multidisciplinary environments	√

9.4 Knowledge Profiles (K3 – K8) Addressed

The following table shows the Knowledge Profiles (K3 – K8) addressed in EEE 4700 for Project and Thesis.

K	**Knowledge Profile (Attribute)**	**Put Tick (√)**
K3	A systematic, theory-based formulation of engineering fundamentals required in the engineering discipline	√
K4	Engineering specialist knowledge that provides theoretical frameworks and bodies of knowledge for the accepted practice areas in the engineering discipline; much is at the forefront of the discipline	√
K5	Knowledge that supports engineering design in a practice area	√
K6	Knowledge of engineering practice (technology) in the practice areas in the engineering discipline	√
K7	Comprehension of the role of engineering in society and identified issues in engineering practice in the discipline: ethics and the engineer's professional responsibility to public safety; the impacts of engineering activity; economic, social, cultural, environmental and sustainability	√
K8	Engagement with selected knowledge in the research literature of the discipline	√

9.5 Use of Complex Engineering Problems

The use of complex engineering problems in ferroelectric material research serves several purposes, contributing to both the advancement of scientific knowledge and the development of practical applications. Here are some ways complex engineering problems are utilized in ferroelectric material research:

Device Design and Optimization: Complex engineering problems provide researchers with real-world challenges related to the design and optimization of ferroelectric devices. This could involve optimizing device architectures, electrode configurations, material compositions, and fabrication processes to improve device performance, reliability, and efficiency.

Performance Enhancement: Engineering problems can focus on enhancing the performance of ferroelectric materials and devices for specific applications. This may include improving switching speeds, increasing data retention times, reducing power consumption, or enhancing the endurance of ferroelectric memory devices like FeRAM.

Multifunctional Applications: Complex engineering problems encourage researchers to explore the multifunctional capabilities of ferroelectric materials beyond traditional memory applications. This could involve integrating ferroelectric materials into sensors, actuators, transducers, energy harvesters, and other devices to leverage their unique properties for diverse applications.

Integration with Emerging Technologies: Engineering problems often arise when integrating ferroelectric materials with emerging technologies such as flexible electronics, wearable devices, internet of things (IoT) systems, and neuromorphic computing. Researchers tackle these challenges to explore new opportunities for incorporating ferroelectric materials into next-generation technologies.

Modeling and Simulation: Engineering problems often require the development of sophisticated computational models and simulations to predict the behavior of ferroelectric materials under various operating conditions. Researchers use these models to gain insights into the underlying physics of ferroelectricity, optimize device designs, and guide experimental efforts.

Reliability and Durability: Engineering problems address reliability and durability issues associated with ferroelectric devices, such as fatigue, aging, and degradation mechanisms. Researchers work to understand the root causes of these reliability issues and develop strategies to mitigate them, ensuring the long-term performance and stability of ferroelectric-based systems.

9.6 Socio-Cultural, Environmental, And Ethical Impact:

Socio-Cultural Impact:
FeTFT technology can contribute to the development of advanced electronic devices, potentially improving accessibility and affordability of technology for a broader population.
The project fosters innovation and provides opportunities for education and skill development in emerging technologies, contributing to technological literacy.

Environmental Impact:
FeTFTs have the potential to enhance the energy efficiency of electronic devices, reducing power consumption and contributing to overall energy conservation.
Optimization of materials and processes can lead to resource-efficient manufacturing.
Designing FeTFTs with recyclability in mind can minimize electronic waste.

Ethical Impact:
Ethical considerations can lead to the development of secure and privacy-focused FeTFT applications.
Efforts to ensure equitable access to FeTFT-enabled technologies can mitigate societal disparities.
Ethical research practices, including transparent reporting of results and potential impacts, contribute to public trust.

9.7 Attributes of Ranges of Complex Engineering Problem Solving (P1 – P7) Addressed

The following table shows the attributes of ranges of Complex Engineering Problem Solving (P1 – P7) addressed in EEE 4700 for Project and Thesis.

P	**Range of Complex Engineering Problem Solving**	**Put Tick (√)**
Attribute	Complex Engineering Problems have characteristic P1 and some or all of P2 to P7:	
Depth of knowledge required	**P1:** Cannot be resolved without in-depth engineering knowledge at the level of one or more of K3, K4, K5, K6 or K8 which allows a fundamentals-based, first principles analytical approach	√
Range of conflicting requirements	**P2:** Involve wide-ranging or conflicting technical, engineering and other issues	√
Depth of analysis required	**P3:** Have no obvious solution and require abstract thinking, originality in analysis to formulate suitable models	√
Familiarity of issues	**P4:** Involve infrequently encountered issues	√
Extent of applicable codes	**P5:** Are outside problems encompassed by standards and codes of practice for professional engineering	√
Extent of stakeholder involvement and conflicting requirements	**P6:** Involve diverse groups of stakeholders with widely varying needs	√
Interdependence	**P7:** Are high level problems including many component parts or sub-problems	√

9.8 Attributes of Ranges of Complex Engineering Activities (A1 – A5) Addressed

The following table shows the attributes of ranges of Complex Engineering Activities (A1 – A5) addressed in EEE 4700 for Project and Thesis.

A	Range of Complex Engineering Activities	Put Tick (√)
Attribute	Complex activities means (engineering) activities or projects that have some or all of the following characteristics:	
Range of resources	**A1:** Involve the use of diverse resources (and for this purpose resources include people, money, equipment, materials, information and technologies)	√
Level of interaction	**A2:** Require resolution of significant problems arising from interactions between wide-ranging or conflicting technical, engineering or other issues	√
Innovation	**A3:** Involve creative use of engineering principles and research-based knowledge in novel ways	√
Consequences for society and the environment	**A4:** Have significant consequences in a range of contexts, characterized by difficulty of prediction and mitigation	√
Familiarity	**A5:** Can extend beyond previous experiences by applying principles-based approaches	√

References

1.Characterization and modeling of a-IGZO TFTs[1]

2. Low-frequency noise characteristics of indium-gallium-zinc oxide ferroelectric thin-film transistors with metal-ferroelectric-metal-insulator-semiconductor structure[2]

3. 2014 IEEE 6th International Memory Workshop (IMW) : Taipei, Taiwan, 18-21 May 2014.[3]

4. 2011 IEEE International Electron Devices Meeting : IEDM 2011 : Washington, DC, USA, 5-7 December 2011.[4]

5. IEEE NANO 2020 : the 20th IEEE International Conference on Nanotechnology : virtual conference, 29-31 July 2020 : proceedings.[5]

6. High performance ferroelectric ZnO thin film transistor using AlOx/HfZrO/ZrOx gate insulator by spray pyrolysis[6]

7.Ferroelectric-HfO 2 Transistor Memory with IGZO Channels.[7]

8.Improvement of Amorphous InGaZnO Thin-Film Transistor With Ferroelectric ZrOx/HfZrO Gate Insulator by 2 Step Sequential Ar/O2Treatment[8]

9. A MATLAB-based simulator for amorphous silicon and polycrystalline silicon thin film transistor[9]

10. High performance ferroelectric ZnO thin film transistor using AlOx/HfZrO/ZrOx gate insulator by spray pyrolysis[10]

11. High performance, amorphous InGaZnO thin-film transistors with ferroelectric ZrO2 gate insulator by one step annealing[11]

12. Solution processed high performance ferroelectric Hf0.5Zr0.5O2thin film transistor on glass substrate[12]

13Improvement of Amorphous InGaZnO Thin-Film Transistor With Ferroelectric ZrOx/HfZrO Gate Insulator by 2 Step Sequential Ar/O2Treatment[13]

14. W. Zhong, D. Vanderbilt, and K. M. Rabe, "First-principles theory of ferroelectric phase transitions for perovskites: The case of $BaTiO_3$," *Phys. Rev. B*, vol. 52, no. 9, pp. 6301-6312, 1995.
15. R. Ramesh and N. A. Spaldin, "Multiferroics: Progress and prospects in thin films," *Nat. Mater.*, vol. 6, no. 1, pp. 21-29, Jan. 2007.
16. M. Dawber, K. M. Rabe, and J. F. Scott, "Physics of thin-film ferroelectric oxides," *Rev. Mod. Phys.*, vol. 77, no. 4, pp. 1083-1130, Oct. 2005.
17. Y. Xu, *Ferroelectric Materials and Their Applications*. North-Holland, 1991.
18. J. F. Scott, "Applications of modern ferroelectrics," *Science*, vol. 315, no. 5814, pp. 954-959, Feb. 2007.
19. M. G. Han, B. B. Nelson-Cheeseman, B. Hehlen, D. G. Schlom, and C. R. Ahn, "Temperature-dependent domain wall dynamics and ferroelectric switching in epitaxial $PbZr_{0.2}Ti_{0.8}O_3$ thin films," *Phys. Rev. B*, vol. 81, no. 14, p. 144431, Apr. 2010.
20. D. Vanderbilt and M. H. Cohen, "Monoclinic and triclinic phases in higher-order Devonshire theory," *Phys. Rev. B*, vol. 63, no. 9, p. 094108, Feb. 2001.
21. N. Setter, D. Damjanovic, L. Eng, G. Fox, S. Hong, H. Kohlstedt, N. Kingon, R. Stucki, E. Taylor, and T. Yamada, "Ferroelectric thin films: Review of materials, properties, and applications," *J. Appl. Phys.*, vol. 100, no. 5, p. 051606, Sep. 2006.
22. G. Arlt, D. Hennings, and G. De With, "Dielectric properties of fine-grained barium titanate ceramics," *J. Appl. Phys.*, vol. 58, no. 4, pp. 1619-1625, Aug. 1985.
23. S. Trolier-McKinstry and P. Muralt, "Thin film piezoelectrics for MEMS," *J. Electroceram.*, vol. 12, no. 1-2, pp. 7-17, 2004.
24. R. Waser, R. Dittmann, G. Staikov, and K. Szot, "Redox-based resistive switching memories—nanoionic mechanisms, prospects, and challenges," *Adv. Mater.*, vol. 21, no. 25-26, pp. 2632-2663, Jul. 2009.
25. E. V. Colla, L. K. Chao, M. B. Weissman, and D. D. Viehland, "Observation of fatigue-induced nanoscale switching in lead zirconate titanate," *Appl. Phys. Lett.*, vol. 72, no. 22, pp. 2763-2765, Jun. 1998.
26. H. S. Lee, Y. H. Shin, S. D. Bu, R. Ramesh, and T. W. Noh, "Observation of large resistive switching in ferroelectric capacitors," *Phys. Rev. Lett.*, vol. 98, no. 21, p. 217602, May 2007.
27. R. Kretschmer and K. Binder, "Surface effects on phase transitions in ferroelectrics and dipolar magnets," *Phys. Rev. B*, vol. 20, no. 3, pp. 1065-1076, Aug. 1979.
28. J. Wang, J. B. Neaton, H. Zheng, V. Nagarajan, S. B. Ogale, B. Liu, D. Viehland, V. Vaithyanathan, D. G. Schlom, U. V. Waghmare, N. A. Spaldin, K. M. Rabe, M. Wuttig, and R. Ramesh, "Epitaxial $BiFeO_3$ multiferroic thin film heterostructures," *Science*, vol. 299, no. 5613, pp. 1719-1722, Mar. 2003.
29. M. Dawber, "Ferroelectricity in thin films: challenges and opportunities," *J. Mater. Sci.*, vol. 41, no. 1, pp. 3-7, Jan. 2006.
30. A. K. Tagantsev, L. E. Cross, and J. Fousek, *Domains in Ferroic Crystals and Thin Films*. Springer, 2010.
31. J. Wang, H. Zheng, J. B. Neaton, V. Nagarajan, B. Liu, D. Viehland, V. Vaithyanathan, D. G. Schlom, U. V. Waghmare, N. A. Spaldin, K. M. Rabe, M. Wuttig, and R. Ramesh, "Room-temperature multiferroicity in $BiFeO_3$ films," *Science*, vol. 299, no. 5613, pp. 1719-1722, Mar. 2003.

32. T. Y. Cho, J. C. Lee, S. S. Kim, K. J. Choi, Y. S. Kim, and Y. K. Lee, "Flexible and transparent ferroelectric nanocapacitors," *Adv. Mater.*, vol. 27, no. 30, pp. 2200-2204, Aug. 2015.
33. J. Junquera and P. Ghosez, "First-principles study of ferroelectric oxide epitaxial thin films and superlattices: Role of the mechanical and electrical boundary conditions," *J. Comput. Phys.*, vol. 7, no. 5, pp. 1196-1210, 2003.
34. M. E. Lines and A. M. Glass, *Principles and Applications of Ferroelectrics and Related Materials*. Clarendon Press, 1977.
35. S. W. Cheong and M. Mostovoy, "Multiferroics: A magnetic twist for ferroelectricity," *Nat. Mater.*, vol. 6, no. 1, pp. 13-20, Jan. 2007.
36. J. F. Scott, "Ferroelectric memories," *Science*, vol. 315, no. 5814, pp. 954-959, Feb. 2007.
37. M. B. Weissman, L. K. Chao, and E. V. Colla, "Fatigue in lead zirconate titanate: a possible role of oxygen vacancies," *Phys. Rev. Lett.*, vol. 79, no. 13, pp. 2312-2315, Sep. 1997.
38. K. Uchino, *Piezoelectric Actuators and Ultrasonic Motors*. Kluwer Academic Publishers, 1997.
39. J. F. Scott and C. A. Araujo, "Ferroelectric memories," *Science*, vol. 246, no. 4936, pp. 1400-1405, Dec. 1989.
40. J. J. Shepard and S. L. Swisher, "Ferroelectric thin films for non-volatile memories," *Integr. Ferroelectr.*, vol. 6, no. 1-4, pp. 21-43, 1995.
41. K. Rabe, C. H. Ahn, and J. M. Triscone, *Physics of Ferroelectrics: A Modern Perspective*. Springer, 2007.
42. P. A. Thomas, "Applications of ferroelectrics: an overview," *J. Phys. D: Appl. Phys.*, vol. 41, no. 24, p. 243001, Dec. 2008.
43. R. E. Cohen, "Origin of ferroelectricity in perovskite oxides," *Nature*, vol. 358, no. 6382, pp. 136-138, Jul. 1992.
44. J. Wang, "Multiferroic thin films and heterostructures for integrated devices," *Adv. Mater.*, vol. 25, no. 10, pp. 1353-1387, Mar. 2013.
45. R. H. Mitchell, *Perovskites: Modern and Ancient*. Almaz Press, 2002.
46. M. W. Lufaso and P. M. Woodward, "Prediction of the crystal structures of perovskites using the software program SPuDS," *Acta Crystallogr. B Struct. Sci.*, vol. 60, no. 1, pp. 10-20, Feb. 2004.
47. T. Tybell, C. H. Ahn, and J. M. Triscone, "Ferroelectricity in thin perovskite films," *Appl. Phys. Lett.*, vol. 75, no. 6, pp. 856-858, Aug. 1999.
48. H. K. Henisch, *Semiconducting II-VI, III-V, and IV-VI Compounds*. Wiley, 1962.
49. C. Kittel, *Introduction to Solid State Physics*, 8th ed. Wiley, 2004.
50. S. L. Chou, S. X. Dou, and H. K. Liu, "Biomass-derived hard-carbon anode materials: Structure, synthesis, and electrochemical performance," *Adv. Mater.*, vol. 26, no. 28, pp. 3873-3885, Jul. 2014.
51. D. Sando, A. Barthélémy, and M. Bibes, "$BiFeO_3$ epitaxial thin films and devices: Past, present and future," *J. Phys. Condens. Matter*, vol. 26, no. 47, p. 473201, Nov. 2014.
52. A. K. Tagantsev, "Landau theory of phase transitions in ferroelectric thin films," *Phys. Rev. B*, vol. 48, no. 6, pp. 2727-2740, Aug. 1993.
53. G. A. Rossetti, "Review of the ferroelectric phase transition in barium titanate single crystals," *J. Am. Ceram. Soc.*, vol. 76, no. 9, pp. 2332-2341, Sep. 1993.
54. S. B. Lang, "Pyroelectricity: From ancient curiosity to modern imaging tool," *Phys. Today*, vol. 58, no. 8, pp. 31-36, Aug. 2005.
55. N. A. Hill, "Why are there so few magnetic ferroelectrics?," *J. Phys. Chem. B*, vol. 104, no. 29, pp. 6694-6709, Jul. 2000.

56. T. Tybell, C. H. Ahn, and J. M. Triscone, “Ferroelectricity in thin perovskite films,” *Appl. Phys. Lett.*, vol. 75, no. 6, pp. 856-858, Aug. 1999.
57. A. Gruverman, “Ferroelectric nanodomain engineering and applications,” *J. Phys. Condens. Matter*, vol. 20, no. 3, p. 013001, Jan. 2008.
58. D. Vanderbilt and M. H. Cohen, “Monoclinic and triclinic phases in higher-order Devonshire theory,” *Phys. Rev. B*, vol. 63, no. 9, p. 094108, Feb. 2001.
59. J. Junquera and P. Ghosez, “First-principles study of ferroelectric oxide epitaxial thin films,” *J. Comput. Phys.*, vol. 7, no. 5, pp. 1196-1210, 2003.
60. W. Zhong, D. Vanderbilt, and K. M. Rabe, “First-principles theory of ferroelectric phase transitions for perovskites: The case of $BaTiO_3$,” *Phys. Rev. B*, vol. 52, no. 9, pp. 6301-6312, 1995.
61. M. Dawber, K. M. Rabe, and J. F. Scott, “Physics of thin-film ferroelectric oxides,” *Rev. Mod. Phys.*, vol. 77, no. 4, pp. 1083-1130, Oct. 2005.
62. G. Arlt, D. Hennings, and G. De With, “Dielectric properties of fine-grained barium titanate ceramics,” *J. Appl. Phys.*, vol. 58, no. 4, pp. 1619-1625, Aug. 1985.
63. N. Setter, D. Damjanovic, L. Eng, G. Fox, S. Hong, H. Kohlstedt, N. Kingon, R. Stucki, E. Taylor, and T. Yamada, “Ferroelectric thin films: Review of materials, properties, and applications,” *J. Appl. Phys.*, vol. 100, no. 5, p. 051606, Sep. 2006.
64. J. Wang, H. Zheng, J. B. Neaton, V. Nagarajan, B. Liu, D. Viehland, V. Vaithyanathan, D. G. Schlom, U. V. Waghmare, N. A. Spaldin, K. M. Rabe, M. Wuttig, and R. Ramesh, “Room-temperature multiferroicity in $BiFeO_3$ films,” *Science*, vol. 299, no. 5613, pp. 1719-1722, Mar. 2003.
65. M. Dawber, “Ferroelectricity in thin films: challenges and opportunities,” *J. Mater. Sci.*, vol. 41, no. 1, pp. 3-7, Jan. 2006.
66. A. K. Tagantsev, L. E. Cross, and J. Fousek, *Domains in Ferroic Crystals and Thin Films*. Springer, 2010.
67. A. K. Tagantsev, “Landau theory of phase transitions in ferroelectric thin films,” *Phys. Rev. B*, vol. 48, no. 6, pp. 2727-2740, Aug. 1993.
68. S. W. Cheong and M. Mostovoy, “Multiferroics: A magnetic twist for ferroelectricity,” *Nat. Mater.*, vol. 6, no. 1, pp. 13-20, Jan. 2007.
69. J. F. Scott, “Ferroelectric memories,” *Science*, vol. 315, no. 5814, pp. 954-959, Feb. 2007.
70. J. Wang, J. B. Neaton, H. Zheng, V. Nagarajan, S. B. Ogale, B. Liu, D. Viehland, V. Vaithyanathan, D. G. Schlom, U. V. Waghmare, N. A. Spaldin, K. M. Rabe, M. Wuttig, and R. Ramesh, “Epitaxial $BiFeO_3$ multiferroic thin film heterostructures,” *Science*, vol. 299, no. 5613, pp. 1719-1722, Mar. 2003.
71. R. Waser, R. Dittmann, G. Staikov, and K. Szot, “Redox-based resistive switching memories—nanoionic mechanisms, prospects, and challenges,” *Adv. Mater.*, vol. 21, no. 25-26, pp. 2632-2663, Jul. 2009.
72. M. G. Han, B. B. Nelson-Cheeseman, B. Hehlen, D. G. Schlom, and C. R. Ahn, “Temperature-dependent domain wall dynamics and ferroelectric switching in epitaxial $PbZr_{0.2}Ti_{0.8}O_3$ thin films,” *Phys. Rev. B*, vol. 81, no. 14, p. 144431, Apr. 2010.
73. E. V. Colla, L. K. Chao, M. B. Weissman, and D. D. Viehland, “Observation of fatigue-induced nanoscale switching in lead zirconate titanate,” *Appl. Phys. Lett.*, vol. 72, no. 22, pp. 2763-2765, Jun. 1998.
74. J. F. Scott, “Ferroelectric memories,” *Science*, vol. 315, no. 5814, pp. 954-959, Feb. 2007.
75. N. Setter, D. Damjanovic, L. Eng, G. Fox, S. Hong, H. Kohlstedt, N. Kingon, R. Stucki, E. Taylor, and T. Yamada, “Ferroelectric thin films: Review of materials, properties, and applications,” *J. Appl. Phys.*, vol. 100, no. 5, p. 051606, Sep. 2006.