FERROIC MATERIALS-BASED TECHNOLOGIES

Edited By
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Preface

Ferroic materials have sparked widespread attention because they represent a broad spectrum of elementary physics and are employed in a plethora of fields, including flexible memory, enormous energy harvesting/storage potential, spintronic functionalities, spin caloritronics, and a large range of other multi-functional devices. Moreover, in multiferroic materials, two or more primary ferroic orderings—such as ferroelectrics; Dia-, Para-, Ferro-, Ferri-, and Antiferromagnetic materials; ferroelastic materials; and ferrotoroidicity as the fourth form of ferroic order—are all present simultaneously in the similar phase. Magnetic materials exhibit significant electro-mechanical coupling, pyro-electricity, and electro-optical characteristics, as well as spontaneous but switchable magnetic behavior, whereas ferroelectric materials exhibit spontaneous but switchable electric polarization.

With the application of new ferroic materials, a strong room-temperature ferroelectricity with high saturation polarization may be established in ferroelectric materials, and magnetism with significant magnetization can be accomplished in magnetic materials. Furthermore, magnetoelectric interaction between ferroelectric and magnetic orderings is high in multiferroic materials, which could enable a wide range of innovative devices. Magnetic, ferroelectric, and multiferroic 2D materials with ultrathin characteristics above ambient temperature are often expected to enable future miniaturization of electronics beyond Moore’s law for energy-efficient nanodevices. This book addresses the prospective, relevant, and original research developments in the ferroelectric, magnetic, and multiferroic fields. Readers of this book will can gain a better understanding of ferroic materials, their related technologies, and their various applications. In fields both specific and related to ferroic materials, this book serves as a great reference tool for students, physicists, academics, researchers, and professionals.

Chapter 1 gives a complete overview of ferroic materials, their history, and the latest progress. It discusses four main types, ferromagnetic, ferroelastic, ferroelectric, and multiferroic materials, while explaining their properties and various applications like data storage, sensors, and more. The chapter also covers the current research pertaining to these materials.

Chapter 2 encapsulates the history and current presence of ferroic materials. This chapter gives details of ferroic materials, e.g., primary and secondary types of ferroic materials. Primary ferroic materials include ferromagnetic, ferroelectric, and ferroelastic, while secondary ferroic materials include multiferroics, ferromagnetoelectric, ferromagnetoelastic, and ferroelastoelectric materials, and all are addressed. The origin of ferroelectricity, ferroelasticity, ferromagnetism, scaling, and recent advances in ferroic materials is also outlined.

Chapter 3 covers an in-depth evaluation of the state of these materials currently and their promising future possibilities. This chapter offers a greater understanding of the possible improvements and applications of ferroic and multiferroic materials in a variety of industries, making it an invaluable resource for researchers and scientists.

Chapter 4 presents a brief history, working principle, theory, and various measurement techniques of electrocaloric effect (ECE) in ferroelectrics. Furthermore, it focuses on different strategies that are adopted to enhance ECE in various lead-based and lead-free ferroelectrics, relaxor ferroelectrics, and hafnia-zirconia-based ferroelectrics.

Chapter 5 discusses the preparation, improvement, and characterizations of ferroelectric and ferroelastoelectric materials. Several synthesis methods for ferroelectric and ferroelastoelectric materials are explained in detail. Improvements and applications of ferroelectric and ferroelastoelectric materials are also discussed.

Chapter 6 examines the elastocaloric impact (ECE) in the discipline of solid-state cooling. Ferroelectric materials are employed for solid-state cooling purposes due to their distinctive thermodynamic features and phase transition uses. Additionally, ECE is further divided into uniaxial and biaxial based on its behavior in the microstructure of materials.

Chapter 7 discusses the flexoeffect alterations in the ferroic nanosystem and their attributes that result from the inhomogeneity of order parameters. This effect exists spontaneously. The equation framework of FCT (flexoelectric coupling tensor) for various point groups using a direct matrix approach, including the quantity of non-zero independent components, is also covered.

Chapter 8 covers recent advancements in ferroic thin films, multi-layers, and hetero-structures, including their historical background, properties, and characterization methods. The significance of atomically controlled thin films and interfaces is emphasized, along with their applications in microelectronics, data storage, sensing, and energy conversion. The chapter also reviews the ongoing research into the enhancement of their characteristics and the expansion of their usage in the future.

Chapter 9 deals with multiferroic materials, their origin, history, and present development, along with the origin of ferromagnetic, antiferromagnetic, and ferroelectric phases. Classification of multiferroics in singlephase and composite multiferroic materials based on their coupling is also addressed. Single-phase multiferroics classification in type I and type II multiferroics and their prominent examples are discussed, as are possible applications, such as magnetic field sensors, memory devices, and laser applications of multiferroics.

Chapter 10 delves into the basic concepts, formation mechanism, phase structure, feasibility, and classifications of ferroic materials. Furthermore, it elaborates on comparing primary and secondary ferroics along with multi-ferroics formation and their relation with both classes of ferroic materials. Applications of these ferroic materials in various fields, including nanotechnology, are also elaborated upon.

Chapter 11 discusses the importance of domain boundary engineering in multiferroic materials and how it affects the properties of these materials. Domain boundary engineering can be used to manipulate the domain structure and affect the interaction between various ferroic orders. The advantages and challenges of domain boundary engineering are also discussed.

In chapter 12, magneto-electric, dielectric, and optical features of ferro/antiferroelectric materials are explained in detail. Polarization curves for 0.96BaTi–0.04BaFO were studied after the samples had been treated at different temperatures. Additionally, dielectric characteristics of La-modified AFE PbZrO3 thin films, BNTC22, PLZST-AFE material and BiMgFeCeO6 are reviewed.

Chapter 13 details the rapid growth in smart electronic and optical devices based on metal-halide perovskites (MHPs), due to their auspicious and innovative semiconducting nature to show ferroelectric behavior. The theoretical and experimental evidence of the ferroic nature of MHPs, the dimension dimension-dependent ferroelectricity within MHPs, and their applications in devices are all covered thoroughly.

We are deeply grateful to everyone who helped with this book and greatly appreciate the dedicated support and valuable assistance rendered by Martin Scrivener and the Scrivener Publishing team during its publication.

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Ferroic Materials: From Past to Present

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Abstract

The chapter provides an overview of the development and applications of ferroic materials. The chapter begins with a brief history of ferroic materials and their discovery and a detailed discussion of the four major types of ferroic materials: ferromagnetic, ferroelastic, ferroelectric, and multiferroic materials. The section on ferromagnetic materials covers their magnetic properties and applications in data storage, sensing, and medical imaging. The section on ferroelastic materials describes their mechanical properties and applications in actuators, sensors, and energy-harvesting devices. The section on ferroelectric materials explains their electrical properties and applications in capacitors, transducers, and memory devices. Finally, the section on multiferroic materials discusses their unique combination of multiple ferroic properties and their potential applications in next-generation devices such as spintronics, magneto-electric sensors, and nonvolatile memory. The chapter concludes by mentioning the present state of research and probable future directions for developing and applying ferroic materials. This chapter comprehensively introduces ferroic

materials, their historical development, and their diverse applications across multiple fields. It will interest researchers, students, and materials science, physics, and engineering professionals.

Keywords: Ferromagnetic, ferroelectric, ferroelastic, multiferroic, piezoelectric sensors, magnetic sensors

1.1 Introduction

Ferroic materials exhibit ferroic ordering, a long-range ordered state in which the material shows a spontaneous polarization, magnetization, strain, or other physical properties. Intense research has been done on these materials over the past few decades due to their potential for various technological applications.

One of the most critical applications of ferroic materials is in the field of data storage. Ferromagnetic materials, for example, are used extensively in hard disk drives, where they store digital information in magnetic domains. Ferroelectric materials, on the other hand, are used in nonvolatile memory devices. One example of a nonvolatile memory device is ferroelectric random access memory (FeRAM). It has faster access times and lower power consumption than conventional memory devices. In data storage, ferroelastic materials have some potential applications because they can undergo reversible strain, and this property can be utilized to develop data storage devices with high-density data [1, 2].

Besides data storage, ferroic materials have found applications in various other fields. For example, ferromagnetic materials are used in motors, transformers, and generators due to their ability to generate a magnetic field.

The study of ferroic materials has a long and rich history, dating back to the discovery of ferromagnetism in lodestones by the ancient Greeks. However, it was in the 1930s that the concept of ferroic materials as a class of materials with similar properties was established. Since then, the field has proliferated with the discovery of new materials and phenomena and the development of new characterization techniques [3].

Recently, ferroic materials came into the limelight due to their potential use in technologies such as nanoelectronics and spintronics. Developing new synthesis and fabrication techniques has caused the formation of new materials with novel properties and functionalities, such as multiferroics, which exhibit more than one type of ferroic ordering. The study of ferroic materials is a crucial research field with a wide range of practical applications across different industries and disciplines. The history of ferroic materials research dates back centuries, and recent developments in synthesis and characterization techniques have led to the discovery of new materials with novel properties and functionalities. The remaining sections of this chapter will provide a detailed overview of the different types of ferroic materials, their properties, and their applications.

1.2 Types of Ferroic Materials

Ferroic materials encompassed various types of ordered materials. Ferromagnetic materials, such as iron and nickel, possessed spontaneous magnetization even without an external magnetic field. Ferroelectric materials, like barium titanate and lead zirconate titanate, exhibited spontaneous electric polarization that could be reversed with an electric field. Ferroelastic materials, including shape memory alloys like Nitinol, showcased reversible deformation and strain. Moreover, multiferroic materials