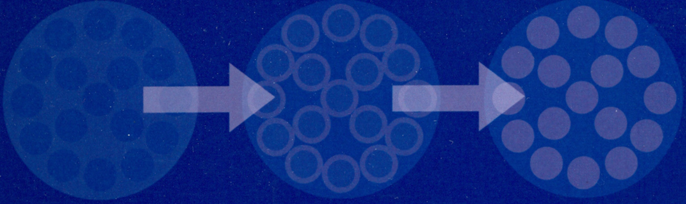
The PHYSICS *of* MULTIFUNCTIONAL MATERIALS

Concepts, Materials, Applications



Martin Gurka

The Physics of Multifunctional Materials

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Preface

THE scope of this book is to explain the physics and materials science underlying multifunctional materials and composites made thereof. The text identifies and elaborates the fundamental principles of ferroelectricity, elastic phase transformation, and energy transfer mechanisms that form the common basis for understanding the functionality, application potential, and limitations of a smart materials system. While these principles are independent of specific kinds of materials or particular applications, they are explained in the context of a representative material and application. That is, the principles apply to whole groups of materials and can be used to differentiate between them. The present book endeavors to cover the basic physics pertaining to multifunctional materials: from mechanics, electrodynamics, thermodynamics, and condensed matter physics, either as a short summary or as applied to selected examples from the large group of multifunctional materials. Familiar physics principles are thus used as a guide to the nature and design of these materials.

The book is not meant to be a comprehensive collection of technical data. Due to the vast progress in research and development, it could never be complete and up to date as a compilation of information. It is intended as a starting point for further reading and as an aid to help readers understand multifunctional materials based on their underlying mechanisms. The book concentrates on three different types of multifunctional materials: piezoceramics, shape-memory alloys, and switchable fluids (electrorheological and magnetorheological fluids). These materials are the best-known commercially available multifunctional materials with the most applications. More interesting in the context of this book is the fact that although the aforementioned examples are all made from very different materials, namely, ceramics, metals, and fluids, respectively, their multifunctionality is based on the same underlying principle—a structural phase transition induced by an external field, either an electrical, magnetic, or thermal field. This is one reason why multifunctional polymeric materials are not discussed. In most cases, polymer multifunctionality relies on mechanisms besides phase transition. Polymer multifunctionality can be related to the different properties of specific components of a compound (e.g., electrically conductive fillers in a thermoplastic matrix) or to the structure of the assembly of a specific device (e.g., the Maxwell stress induced by attracting electrodes leading to the actuation of an electroactive polymer device).

The book follows a straightforward path from the definition and classification of multifunctional materials and their differences from classic materials in chapter two, through a more quantitative approach in chapter four. In chapters five to seven, the principles behind the functionality of piezoceramics, shape memory alloys, and switchable fluids are covered. Chapter three summarizes key points of the physics referred to in this text.

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CHAPTER 1

Introduction

MECHATRONICS, smart structures, and structronics or adaptronics are all different names for a rapidly advancing field of research and development encompassing the development of highly integrated products with adaptive behavior, i.e., the ability to react autonomously to different operating conditions. This includes all functions of a traditional control loop: a structure with sensors, controller, actuators and an energy supply. To reduce the complexity of the final product, as many functions as possible (e.g., sensing and actuation) are integrated into a single element or, even better, are integrated into the material itself. The goal is to develop structures with optimized light weight, reduced space requirements, and a minimum use of energy or materials resources during their whole lifecycle. Industrial applications are multiplying and will continue to do so.

Smart or multifunctional materials form a central element of this new technology, playing the role of a “system enabler” for this new technology and are having an ever larger economic impact. Mastering the engineering and processing of multifunctional materials into smart products are critical challenges for tomorrow’s industry. Standard development scenarios of today will need to change, so that separate disciplines like materials sciences, mechanical design, electronics, and system integration can merge and work as a unit, Still, one point will remain true: the functionality of new products will be achieved by the material they rely on. This means more complex materials’ properties have to be understood by design engineers and be analyzed right from the beginning of the development of a new product. Materials properties in the final product are strongly dependent on processing. Even with well-established processes it must be considered that multifunctional materials have much more complex properties in regards to their design and fabrication, as well as eventual application. Therefore, the product development process can no longer be split into discrete tasks executed sequentially by mechanical engineers, process engineers, and systems specialists. For example, the standard approach of adding sensors or actuators to a mechanical system, will be replaced by designing from scratch a smart materials system with integrated functionality. The whole development process will come to reflect a connection to the diverse, yet related, properties required to create a multifunctional material.

CHAPTER 2

Multifunctional Materials or Smart Materials versus Normal Materials

LOOKING through the literature, one will find lots of different names used synonymously for the topic of this book. *Functional materials, multifunctional materials, smart materials* and *adaptive materials* are the most common. Considering the peculiarities of these materials and their difference from normal structural materials, like steel or ceramics, we will see that the term *multifunctional material* best represents what is meant by all the other names. It will be used throughout this book, with the understanding that it covers what is meant by all its synonyms mentioned above.

Trying to use traditional categories like metals versus polymers or solids versus fluids does not lead to a useful differentiation from normal materials because one finds multifunctional variants in all of these categories. In this chapter we will look into the general definition of this new class of multifunctional materials and find out if there are similarities between different multifunctional materials like metals, ceramics polymers or fluids, which can both lead to a general definition and properly differentiate between them.

If traditional categories from materials sciences like metals, polymers, solids or fluids, which were derived from basic physical or chemical properties of these materials, are not useful in arriving at a definition of multifunctional materials, what categories should be used? From the title of this book one can infer that these might be borrowed from physics.

But before going into more detail and looking for a physically derived definition of multifunctional or smart materials, it is worth having a look into the history of this field of research. It was Robert Newnham who, in a series of lectures and articles, gave useful descriptions of what smart materials are and how their smartness connects to multifunctionality [1–3]. In his definitions, he distinguishes between “smart” materials and “very smart” materials. The difference between smart materials and very smart materials derives from the mechanism of how a smart material in general connects an input signal (e.g., an electric field or a temperature) to an output reaction (e.g., a change in length or an electric current). For normal smart materials, there is a fixed coupling mechanism that is defined by the structure of the material. For very smart materials, this coupling mechanism can be tuned during the application by an additional stimulus (an applied electric field or a mechanical stress, for example).

So, it is not only the title of the present book that suggests physics may be suitable to give a definition of multifunctional materials or to help one understand what makes them different from “regular” materials. The various coupling mechanisms mentioned above are also a good starting point to give a definition and to differentiate among types of multifunctional materials themselves.

In addition, we will examine multifunctional materials from two other general points of view: the special role of multifunctional materials in more complex systems or applications, e.g., how they are the enabling element of an active suspension or a vibration-absorbing system in vehicles and how the multifunctionality of the materials affects their economic impact in commercial applications.

2.1. GENERAL DEFINITION OF MULTIFUNCTIONAL MATERIALS FROM A PHYSICAL ASPECT

Multifunctional materials are most often used as sensors or actuators. This stems from their ability to change measurably at least one physical property or to transmute one form of energy into another when exposed to an external stimulus. These behaviors form the basis for defining multifunctional materials and for furnishing a rough classification of them.

The cause of the behavior in almost all multifunctional materials is the occurrence of at least two structural phase transitions. Below a certain temperature, the microstructure of the material undergoes a displacing and ordering phase transition, where atoms in the crystal structure of the material change places. In the case of piezoelectric materials, this phase transition from a cubic structure with a high symmetry to either a tetragonal or a rhombohedral structure with a lower symmetry happens at the so-called Curie temperature (see Figure 2.1). For shape-memory alloys, the phase transition is called the austenitic phase transition, where the material increases its ordering from an unordered high-temperature phase to the more-ordered austenite phase exhibiting a cubic symmetry. The commonality of these multifunctional materials is a microstructure that after this first phase transition exhibits a strong coupling to an external driving force, an electric or magnetic field or an elastic stress, which triggers a second phase transition that gives rise to the actual multifunctionality of the material. In the case of a shape-memory alloy, for example, the temperature-induced martensite-to-austenite or the stress-induced austenite-to-martensite phase transition are responsible for the shape-memory effect or the superelasticity of the material.

The ferroelastic phase transition of piezoelectrics and the thermoelastic phase transition of shape-memory alloys will be discussed in more detail in Chapter 5.

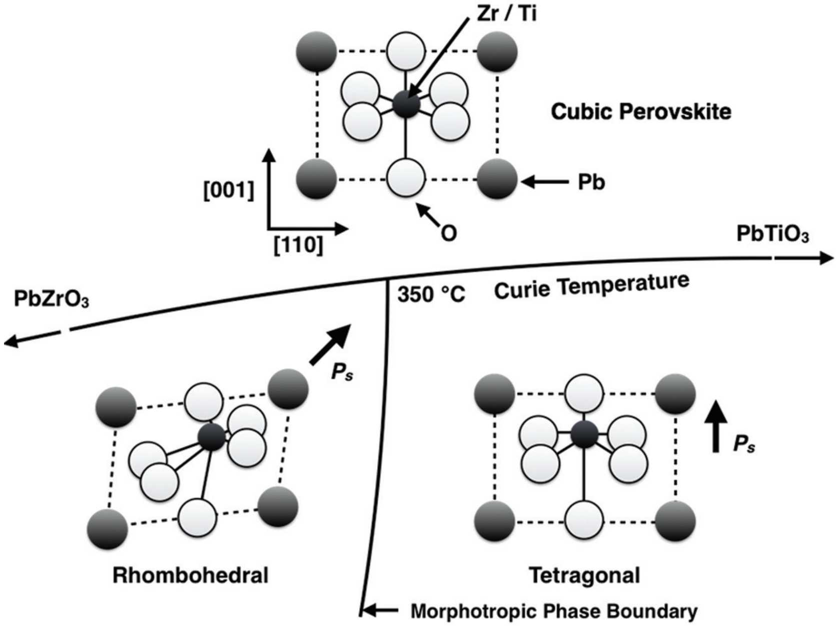

FIGURE 2.1. *Part of the phase diagram of $PbZrO_3$ – $PbTiO_3$, the ferroelectric ceramic PZT. Depicted are the structural changes at the Curie temperature (T_c) and the morphotropic phase boundary. PZT ceramics with a composition near the morphotropic phase boundary exhibit a strong piezoelectric effect because they have 14 possible poling directions (after [1]).*

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