

## Preface

The idea of creating a book of this genre came with the realization that there were no books in the open literature that combined the materials aspect of piezoelectric and acoustic materials together with the principles of transducer design and recent advances in piezoelectric transducers, as well as their application. By combining topics such as Fundamentals of Piezoelectricity (Part I), Piezoelectric and Acoustic Materials for Transducer Technology (Part II), Transducer Design Principles (Part III), and Piezoelectric Transducer Fabrication Methods (Part IV), our purpose was to provide a comprehensive and self-consistent volume whereby the aforementioned lack of a reference book in the open literature can be remedied.

This book is comprised of four complementary sections. In Part I, a concise treatment of piezoelectric phenomena in solids is presented. Chapter 1 by Akdoğan and Safari establishes the solid-state thermodynamic foundation for ferroelectricity as all piezoelectrics used in today's transducer technology are ferroelectric. It also delineates the origin of very important concepts such as spontaneous polarization, hysteresis loops, and piezostress coefficients, which are needed to describe the macroscopic behavior of piezoelectrics. The chapter by Kholkin, Pertsev, and Goltsev (Chap. 2) deals with the symmetry aspects of the piezoelectric effect in various materials (single crystals, ceramics, and thin films). It defines the third-rank tensor of piezoelectric coefficients in reference to the fundamentals of crystallography, and then discusses the orientation dependence of the longitudinal piezoelectric response in ferroelectric single crystals. Also, a concise discussion on the effective piezoelectric constants of polydomain crystals, ceramics, and thin films and their dependence on crystal symmetry is provided. The domain-wall contribution to the piezoelectric properties of ferroelectric ceramics and thin films is also given. Finally, the crystallographic principles of piezomagnetic, magnetoelectric, and multiferroic materials are presented. In Chap. 3, Trolier-McKinstry presents a detailed description of the crystallochemical principles of ferroelectricity and piezoelectricity in solids. The discussion covers perovskites, tolerance factors, domains and domain walls, the lead zirconate titanate (PZT) system, bismuth-layer

structure,  $\text{LiNbO}_3$ , tungsten bronze structure, and  $\text{SbSI}$ , which is the point of departure in the development of piezoelectric composites. The emphasis is on the atomic arrangements leading to polarization and its consequences on material properties.

In Part II, three chapters are devoted to the most prominent piezoelectric and acoustic material systems currently either in use or in development for transducer applications. Damjanovic (Chap. 4) gives a detailed account on lead-based ferroelectrics/piezoelectrics, including  $\text{PbTiO}_3$ , PZT, relaxor ferroelectrics, and single crystals. Therein, one could find an in-depth discussion of the morphotropic phase boundary in the PZT system as well as the anisotropy in piezoelectric response in  $\text{PbTiO}_3$ . Systems with compositional modifications are treated as well, where hard and soft ferroelectrics are introduced. Kosec et al. (Chap. 5) gives a full overview of the  $(\text{K}, \text{Na})\text{NbO}_3$  system, which is the most important lead-free ferroelectric system whose compositional modifications have great promise for applications in the future. The emphasis is on the processing of ceramics such as  $\text{KNbO}_3$ ,  $\text{NaNbO}_3$ ,  $(\text{K}, \text{Na})\text{NbO}_3$ , and the recently discovered KNN–LT–LS ternary system, thereby effectively establishing processing-property relations. Also, a wealth of material properties appertaining to the  $(\text{K}, \text{Na})\text{NbO}_3$  and related systems are included therein. Chap. 6 by Takenaka is on bismuth-based ferroelectric ceramics, which is another lead-free system of utmost importance. The major focus there is on the  $\text{Bi}_4\text{Ti}_3\text{O}_{12}$  and its compositional modifications. Most importantly, Takenaka provides a very thorough treatment of grain orientation (texturing) of such lead-free ceramics, and discusses its consequences on piezoelectric properties. Cheng et al. (Chap. 7) presents a very detailed overview of the advances in electromechanically active polymers in the context of mechatronics and artificial muscle. After a concise review of the appertaining phenomenology on electromechanical behavior in solids, he and his colleagues present systems such as PVDF,  $\text{P}(\text{VDF-TrFE})$  copolymer, and terpolymers. A very comprehensive discussion on phase transitions, structure, and electromechanical response is provided along with sets of material properties. In Chap. 8, Yamashita et al. introduce the recent advances in acoustic lens materials and provide a systematic account on recent advances in silicon-based technologies. Therein, the evolution of acoustic properties of silicon lenses are discussed from the processing vantage point, and the most prominent dopants for composite-making are identified. Part II ends with another chapter on acoustic lens materials by Kondo, which summarizes the use of carbon fiber composites and how a wide range of acoustic impedances can be fashioned for transducer applications.

Part III is devoted to transducer design principles. First, Lethiecq et al. (Chap. 10) discuss the design principles governing medical ultrasound transducers. The performance metrics of such transducers are introduced, operation principles of single element and transducer arrays are elaborated on, and the underlying acoustic principles are discussed. In Chap. 11, Tressler discusses the design principles of transducers for sonar applications. Various in-air and under-water calibration techniques are first presented, followed by various projector designs (ring, bender bar, flexural disks, flextensional, tonpilz) are introduced and appertaining design methodologies are elaborated on. Also included in that chapter are hydrophone design principles, including cylinder and sphere configurations. This section ends

with Chap. 12, where Hladky-Hennion provides a comprehensive overview of finite element modeling (FEM) principles as applied to piezoelectric transducers. First, the mathematical foundations are provided through constitutive equations, the variational principle, and appertaining functionals. Then, the application of the FEM method is demonstrated. Analysis methods such as static, harmonic, modal, and transient are given. The chapter concludes with examples on the analysis of cymbal transducers and cymbal arrays, and 1–3 composite transducers.

Part IV is on transducer fabrication methods. Therefore, it is inherently tied into applications as well since fabrication methods tend to be application specific. In Chap. 13, Schoenecker addresses the status of piezoelectric fiber composite fabrication, and focuses on three topics: the preparation of sol–gel-derived PZT fiber/polymer composites, the soft-mold method with high achievement potential for preparing tailor-made composites and understanding the structure–property relationships, and the preparation of powder suspension-derived PZT fiber/polymer composites as the technologically advanced and commercialized process. Therein, it is iterated that the use of piezoceramic fibers allows for the fabrication of high-quality fiber composites, surpassing performance metrics that cannot be achieved by the conventional dice and fill technique. Beige and Steinhausen (Chap. 14) discuss different types of composition gradient systems for bending actuators. The combination of hard and soft piezoelectric ceramics and electrostrictive and electroconductive materials are introduced. Processing strategies are summarized and a mathematical models for modeling of poling in such combined systems are presented. The results of theoretical analysis are compared with experimental data for lead-free systems based on barium titanate. In Chap. 15, Smay et al. present the advances made in the use of robocasting solid freeform fabrication (SFF) technique based on the direct writing of highly concentrated colloidal gels. They show that robocasting offers facile assembly of complex three-dimensional geometries and a broad pallet of ceramic, metallic, and polymeric materials from which devices can be developed. Examples of PZT skeletons for direct use or to create epoxy-filled composites suitable for hydrostatic piezoelectric sensors are given. PZT composites of (3–3, 3–2, 3–1) connectivity are demonstrated. It is shown that the figure of merit ( $d_{hg_h}$ ) increases by up to 60-fold compared with bulk PZT in such composites. In Chap. 16, Jantunen et al. present a comprehensive overview of the general properties and requirements of piezoelectric micropositioners. Special attention is paid to stiffness related to other actuator properties, with general rules and examples. Also the control and sensor techniques required to avoid or minimize the nonlinearities of the piezoelectric device are discussed in detail. And it is shown that in micropositioning a profound overall know–how about material properties, actuator design, and control, sensor and driving techniques are required in addition to an in-depth knowledge of application requirements. Finally, some commercial applications utilizing piezoelectric micropositioners are given as examples. Doğan and Uzgur (Chap. 17) present a broad review of the application of piezoelectric transducers. Piezoelectric actuators are compared with magnetically active and thermally active actuators, and then piezoelectric actuators and their design and fabrication, especially traditional piezoelectric transducers with newly designed flextensional transducers, are compared.

Finally, application-related issues are discussed on Chap. 18 by Shashank et al. provides strategies for the selection of the piezoelectric transducers based on the frequency and amplitude of the mechanical stress in the context of energy harvesting. The figure of merit for the material selection is shown to be directly proportional to the product ( $d \times g$ ). The criterion for maximization of the product is discussed in depth, and results are reported on various devices utilizing piezoelectric bimorph transducers. Or and Chan (Chap. 19) present recent advances in piezocomposite ultrasonic transducers for high-frequency wire bonding of semiconductor packages. The principles of wire-bonding and appertaining challenges are summarized. The use of 1–3 piezocomposite rings in such applications is shown, and the electro-mechanical characteristics are presented. The chapter also includes a section on the evaluation of wire-bonding performance utilizing such transducers. Bassiri-Gharb (Chap. 20) presents the use of piezoelectrics in MEMS applications. In that chapter, the properties of AlN, ZnO, PZT, and PMN–PT films are reviewed, and the effect of substrate clamping is briefly discussed. Then fabrication and integration issues are addressed. Various applications of piezoelectrics, including AFM probe tips, RF switches, micromirrors, micropumps, and microvalves are given. In Chap. 21, Shung et al. discuss high-frequency ultrasonic transducers and arrays. After a thorough overview of the state of the art, LiNbO<sub>3</sub> single-crystal transducers, and PMN–PT single-crystal needle transducers for Doppler flow measurements are presented. A multitude of transducer designs are shown (annular arrays, linear arrays, and their derivatives), and underlying processing issues are elaborated on. The last chapter of the section and the book is on micromachining of piezoelectric transducers by Pappalardo et al. (Chap. 22). The basic principles, the fabrication processes, and some modeling approaches of novel micromachined ultrasonic transducers (MUTs) are described. It is shown that these transducers utilize the flextensional vibration of an array of micro-membranes called cMUT (capacitive MUT). It is also shown that good echographic images of internal organs in the human body have been obtained, demonstrating the possibilities of this technology to be utilized in commercial 1D and 2D probes for medical applications.

In conclusion, we thank all the contributing authors for their great zeal and industry in composing their respective chapters. Were it not for their willingness to participate in this exciting project, none that was accomplished could have been possible. A project of this magnitude cannot see the light of day without a constant source of encouragement and support. To that end, we express our gratefulness to our families, friends, and colleagues. Last but not the least, we thank Springer for giving us great flexibility in regard to the size of this volume.

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