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Modern Piezoelectric Energy-Harvesting Materials

Springer

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To our colleagues, friends and pupils

Preface

> Energy is the capacity for doing work. It may exist in potential, kinetic, thermal, electrical, chemical, nuclear, or other various forms… Energy can be converted from one form to another in various ways. Usable mechanical or electrical energy is, for instance, produced by many kinds of devices, including fuel-burning heat engines, generators, batteries, fuel cells, and magnetohydrodynamic systems.
>
> Encyclopædia Britannica

> But do not try to keep what Providence
> Has given you, for your own use alone:
> We're doomed—and we all know it perfectly
> To squander not hoard the wealth we own.
>
> A. Akhmatova

An increasing interest in autonomous devices and electrical accumulators promoted by industrial and domestic applications has raised the issue of powering these systems. In the past decade, the important trend to address this problem consists in using ambient energy from the environment to supply autonomous devices and to make them self-powered with sufficient energetic concentration for various applications. Among the ambient-energy sources to be of interest, one can mention solar, thermal and mechanical sources. Despite this variety, much attention is paid to using mechanical energy, whose sources are available for small-size piezoelectric systems. Mechanical ambient energy to be taken from nature and converted into electrical energy is usually associated with strong winds, sea waves, sounds (acoustic waves) and earthquakes. A conversion of the mechanical form of energy into the electrical form implies using piezoelectric materials due to their sufficiently high energy densities, various electromechanical properties and performance in piezoelectric transducers, sensors, self-powered small-scale devices, hydrophones, etc.

In the past decade, rapid growth in the energy-harvesting field has been obvious, and thereafter the term '*piezoelectric energy harvesting*' has become widespread in the society of scientists and engineers. Piezoelectric energy harvesting is based on the direct piezoelectric effect at which electrical charge (or polarisation of a piezoelectric element) is generated from an external mechanical stress, strain, acoustic wave, vibration sources and so on. It should be added that the piezoelectric effect is concerned with one of three physical mechanisms of vibration-to-electric energy conversion. Along with the piezoelectric effect, electrostatic and electromagnetic transduction may be effective at this conversion, but to a lesser degree. A piezoelectric harvester can transform kinetic energy from mechanical vibrations into electrical energy due to the piezoelectric effect, and therefore, piezoelectric coefficients concerned with this effect should influence energy-harvesting characteristics of every piezoelectric harvester. Its important feature is that the geometric configuration and sizes of the piezoelectric harvester can be varied in wide ranges, and therefore, the system can be exploited on either a macro-scale or micro-scale level.

Among materials that meet conditions for piezoelectric energy-harvesting applications, in the first line we should highlight poled ferroelectric ceramics and composites based on either ferroelectric ceramics or relaxor-ferroelectric single crystals with high piezoelectric activity. Due to various adaptive characteristics, high piezoelectric performance and possibilities to vary and tailor their electromechanical properties in external fields, the aforementioned composites have been regarded as an important group of smart materials. Undoubtedly, complex and intricate interconnections between microstructure, composition and physical properties of the composites stimulate studies to predict and interpret the properties and related parameters of these materials under various conditions.

In the present monograph we discuss the piezoelectric performance and related parameters that are to be taken into consideration at piezoelectric energy harvesting. In particular, it provides a complex analysis of the *microgeometry–properties* relations in modern piezo-active composites, and this analysis broadens the traditional material-science concepts on the *composition–structure–property* relations and may be a stimulus to create novel high-effective materials with the predictable properties. Important examples of the piezoelectric performance of the composites or ceramics are discussed in the context of their anisotropy, piezoelectric sensitivity, electromechanical coupling, figures of merit and so on. The novelty of the monograph consists in the first systematisation of many authors' results on the performance of modern piezoelectric materials in the context of energy-harvesting applications.

The present monograph has been written on the basis of the authors' research results obtained at the Southern Federal University (Russia) and University of Bath (United Kingdom). The academic style of presentation of the research results and the discussion about these results indicate that this monograph would be useful to engineers, postgraduate students, researchers, and lecturers, i.e., to many specialists working in the field of smart materials, dealing with their effective electromechanical properties and applications. This monograph will be of benefit to all specialists looking to understand the anisotropic electromechanical properties and their links to piezoelectric energy harvesting, its parameters and applications. Some chapters and sections of the monograph may be a basis for a university course devoted to piezoelectric (or ferroelectric and related) materials and their energy-harvesting characteristics. Introducing this new monograph, we would like to mention lines from '*The Reader*' by A. Akhmatova as follows:

Each reader's a treasure-trove hidden
In fathoms of earth—even if
He is undistinguished, unbidden,
And has been mute all of his life.
And buried there, everything lies
That nature deems best to conceal…

Based on our knowledge, experience and new research results, we hope that the twenty-first century termed *The Century of New Materials and Technologies*, will lead to the fruitful development of new scientific directions in the field of piezoelectric energy harvesting and will promote creation of novel high-effective piezoelectric materials for energy-harvesting and related applications.

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Contents

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Christopher Rhys Bowen was born on 18 January 1968 and grew up in Beddau, South Wales (UK). He earned a BSc (First Class) in Materials Science at the School of Materials, University of Bath, UK, in 1990 and worked on his DPhil thesis in ceramic manufacture under the supervision of Prof. Brian Derby in the Department of Materials, University of Oxford, UK, in 1990–1993 (Ph.D. awarded in 1994). In 1993–1994, he worked as researcher in the Advanced Ceramics Group at the Technical University of Hamburg-Harburg (TUHH), Germany, under the supervision of Prof. Nils Claussen. From 1994 to 1996, he was research fellow at the School of Materials, University of Leeds, UK, working with Prof. Ron Stevens. From 1996 to 1998, he was Senior Scientist at the Defence Evaluation and Research Agency (DERA), Functional Materials Group, UK, working on ferroelectric ceramics and composites. He joined the University of Bath, UK, in August 1998, and is now a professor at the same university.

The research interests of Dr. C.R. Bowen are concerned with modern functional materials, including ferroelectric ceramics and piezo-active composites for modern sensors and actuators, as well as with manufacturing and characterisation of these materials. Continuing interest includes the use of piezoelectric materials, nanostructured materials and porous materials for energy harvesting and water splitting applications. Additional interest is concerned with pyroelectric materials, their performance and use in energy-harvesting applications. Dr. C.R. Bowen earned the Thornton and Hazelwood prizes for academic work (1986–1990), Institute of Materials National Lecture Competition award (1993), SET award (2002), and John Willis award for excellence in research and teaching (2003). Dr. C.R. Bowen has published over 230 scientific papers, conference proceedings, and abstracts. He has been awarded an ERC Advanced Fellowship in Novel Energy Materials, Engineering Science and Integrated Systems (NEMESIS, Grant Agreement No. 320963), and this support is greatly acknowledged.

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Honorary co-worker of Higher Professional Education of the Russian Federation (Ministry of Education and Science of the Russian Federation, Moscow, Russia, 2009). Wilhelm Leibniz Medal for Achievements in Technical and Physico-Mathematical Sciences (2014), Gold Medal "European Quality" (2014) and Medal to the 100th Anniversary of the Southern Federal University (2015). Member of the International Biographical Centre Top 100 Educators (Cambridge, UK, 2010) and Top 100 Scientists (Cambridge, UK, 2012). Biographical data by Dr. Vitaly Yu. Topolov have been published in "Dictionary of International Biography" (*IBC*, Cambridge, UK), "2000 Outstanding Intellectuals of the 21st Century" (*IBC*, Cambridge, UK) and "Who's Who in the World" (*Marquis*, New Providence, USA).

Hyunsun Alicia Kim was born on 17 December 1974 in Seoul, Korea. She received a BEng (1997) and Ph.D. (2001) from the Department of Aeronautical Engineering, University of Sydney, Australia. Her Ph.D. research was in topology optimization, and its significance in the research field was recognised by the Zonta International Amelia Earhart Award. She continued the research in computational mechanics and structural optimisation at the University of Warwick (UK) and Virginia Tech (USA). She began her academic career as a Lecturer in 2001, subsequently Senior Lecturer then Reader in the Department of Mechanical Engineering, University of Bath, (UK). Since 2015, she is an Associate Professor in the Structural Engineering Department, University of California, San Diego (USA). She has been a visiting research scholar at NASA Langley and an affiliate of the Los Alamos National Laboratory.

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