Power Harvesting via Smart Materials

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Contents

Foreword I

The invention of electricity and the lightbulb has played a ground-breaking role in the development of modern technology and society. Piezoelectric materials, one of the so-called “smart materials,” produce an electric charge upon the application of stress; this fascinating characteristic allows them to be exploited to generate electric energy via the use of ambient mechanical vibrations in machinery and biological systems. Sensors are being increasingly used in a range of applications: structural health monitoring (SHM), security networks, medicine, and aeronautics to civil engineering, military, and animal tracking. The recent development of lower-power electronic devices, such as wireless sensor nodes, active RFIDs, and nano-transducers, has led to an increase in the demand for piezoelectric energy-harvesting applications to power these sensors. Energy harvesting is of interest to all of us because it reduces the task of replacing conventional batteries in self-powered devices located in remote and difficult-to-access locations.

This monograph contains the most comprehensive and up-to-date review of ambient electric energy harvesting via piezoelectric, ferroelectric, and pyroelectric materials. It brings to both novice and advanced readers all of the topics required to understand piezoelectric energy-harvesting techniques. The text presents the complete lifecycle of a material from the basics of smart materials, theory of operation of harvesters, and structure of piezoelectric materials to the processing and technological applications in a systematic manner with emphasis on the most recent advances. It also contains instructive case studies and examples of experimental validation of novel energy-harvesting techniques. This monograph should prove to be of immeasurable benefit for graduate students, engineers, and scientists as a comprehensive guide to the current state-of-the-art science and technology of the analysis and development of piezoelectric energy harvesting.

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Professor of Materials
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Foreword II

I congratulate the authors for having written this timely and excellent monograph. Energy harvesting remains a topic of intense interest in academic and industrial settings because it provides a route to achieve an autonomous power supply for low-duty-cycle electronics. Dr. A. K. Batra is a prolific scholar, author, and accomplished researcher who has authored a monograph on pyroelectric materials in the past. He has contributed significantly to the advancement of knowledge in this area of inquiry and other related fields. We are fortunate to have an individual with his diverse expertise on the faculty of Alabama A&M University, and we are highly appreciative of the fact that he has been able to devote extra time and effort for the preparation of this monograph. I am sure it will prove to be interesting, thought-provoking, and helpful in spurring further progress in this fascinating and challenging field.

I have no doubt that this book will be a success and encourage them in the future.

Chance M. Glenn, Sr.
Professor and Dean
College of Engineering, Technology, and Physical Sciences
Alabama A&M University

Preface

This monograph on ambient energy harvesting consists of ten chapters, organized as follows:

- Chapter 1 explains green energy technologies and their applications. The sources of ambient energies accessible with available commercial devices are discussed.
- Chapter 2 gives a brief overview of dielectrics, the nature of a unique class of smart materials (i.e., ferroelectrics, piezoelectrics, and pyroelectrics), and its classification on the basis of crystal classes. A list of important materials is given, as well as their applications. Piezoelectric/pyroelectric/ferroelectric phenomena are described in the context of their energy-harvesting applications.
- Chapter 3 involves the mathematical modeling of constitutive equations, mechanisms of piezoelectric energy conversion, and the operating principle of a piezoelectric energy-harvesting system. It also focuses on the dielectric, piezoelectric, mechanical, and pyroelectric properties of candidate piezoelectric and pyroelectric materials: from single crystals (such as PMN-PT) to ceramic PZT and polymers (such as PVDF). Recent important literature on piezoelectric energy harvesting is also reviewed.
- Chapter 4 discusses the parametric identification and measurement techniques for piezoelectric energy harvesters, including the efficiency and the physical properties of piezoelectric, ferroelectric, and pyroelectric materials.
- Chapter 5 demonstrates the principles of a piezoelectric cantilever beam for vibrational energy harvesting. Various configurations of cantilever-based energy harvesters are described, as well as the respective modeling used to predict their performance. Various important cantilever structures with multiple piezoelectric elements are reviewed.
- Chapter 6 describes various strategies and techniques that have been developed to enhance piezoelectric energy-harvesting efficiency, namely, the frequency tuning and bandwidth widening of harvesters.

- Chapter 7 briefly describes some of the important devices for piezoelectric power harvesting that have potential applications in the real world.
- Chapter 8 focuses on the fundamentals and principles of energy harvesting via the linear and nonlinear properties of pyroelectrics/ferroelectrics. An overview of various materials and techniques investigated for energy harvesting, including mathematical modeling, is also presented. A survey of recent work on ferroelectric/pyroelectric energy harvesting is reviewed and presented.
- Chapter 9 describes the methodology of the growth and fabrication of important piezoelectric and ferroelectric materials in various forms, such as bulk single crystals, polycrystalline ceramics, thin films, thick films, and composites. Based on the applicability and requirements of the materials, techniques such as a low-temperature solution and melt crystal growth, sputtering, laser ablation, chemical-vapor-deposition techniques, solution-deposition techniques (such as sol-gel, metallo-organic, and spin-coating pyrolysis), and screen printing are illustrated with diagrams and processes via flowcharts.
- Chapter 10 projects a future outlook for piezoelectric energy harvesting.
- The Appendix lists the MATLAB code for a few examples in Chapter 5.

For all technical contacts, suggestions, corrections, or exchanges of information, the reader is advised to contact the authors via email: ashobatra@gmail.com and Lovephy85@gmail.com.

Ashok K. Batra
A. A. Alomari
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Acknowledgments

Ashok K. Batra

First and foremost, this monograph would not be possible without the inspiration of my dear father, who advised me to write this demanding scientific resource. I express my gratitude to him and my late mother for instilling important traits in me, such as perseverance, hard work, and humility. I am forever indebted to my lovely wife, Nutan, my lifeline, for her constant prayers and her perseverance in staying by my side through thick and thin with total love, dedication, and encouragement. I am eternally grateful to my close-knit family, including my adorable younger brother, Vijay, and my uncle, Mr. V. K. Batra, who has supported me wholeheartedly throughout my career and in authoring this monograph. It is virtually impossible to fully express my gratitude to my admirable uncle and aunt, and cousin brothers—Dr. S. K. Grover and Mrs. Manjula Grover, Dr. Kunal Grover, and Dr. Keshav Grover—for their unwavering help in all aspects of my life. I am grateful to Prof. R. B. Lal and Prof. S. C. Mathur for sharing their valuable insights and guidance. A special thanks to Dr. Amar Bhalla for our many stimulating discussions on pyroelectric materials and for his wide knowledge of materials science.

I feel privileged to have worked with eminent teachers, including Prof. S. C. Mathur, the late Prof. A. Mansingh, and Prof. N. K. Bansal. I have benefited from their scientific knowledge and philosophies. I would especially like to thank Dr. Chance Glenn, Sr., Dean of the College of Engineering, Technology, and Physical Sciences at AAMU, for his support and, in particular, our fruitful discussions on energy harvesting. I am grateful to Dr. M. D. Aggarwal for his total support, suggestions, and encouragements. I would like to express my appreciation to the university administration, and the faculty and staff of the Physics department for their general support and the friendly atmosphere that they create. Special thanks to Drs. Matthew Edwards, Anup Sharma, Kamala Bhat, Arjun Tan, and B. R. Reddy for their encouragement. I would also like to give a special thanks to Mrs. Sheral Carter for her excellent cooperation and assistance in graphic design.

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A. A. Alomari

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I also would like to express my sincere gratitude to my parents, brothers, and sisters who provided endless motivation and collaboration during my journey. I owe special thanks and appreciation as well to my wife for her patience and support over the years. I hope that one day she can read this book and understand why I spent so much time in front of my computer.

Thanks to all of my friends for sharing my happiness when I started this project and followed with encouragement when it seemed too difficult to be completed. I would have probably given up without their support and example of what to do when you really want something.

Both authors wish to acknowledge the valuable contributions of the peer reviewers who helped improve the quality, coherence, and presentation of the chapters. Special thanks to Mr. Scott McNeill for meticulously editing the monograph.

Glossary of Symbols and Abbreviations

$1/C$	Stiffness (LPM)
A	Capacitor plate area
A	Electrode surface area
ABX_3	Perovskite structure
AC	Alternating current
AFM	Atomic force microscopy
Ag	Silver
Ag-NP	Silver nanoparticles
Al	Aluminum
$AlPO_4$	Aluminum phosphate (berlinite)
B_r	Frequency parameter of the r^{th} mode
$BaTiO_3$	Barium titanate
C	Capacitance
c'	Volume specific heat
c_1	Primary oscillator damping coefficient
c_2	Secondary oscillator damping coefficient
c_3	Third oscillator damping coefficient
c_a	Viscous air damping coefficient
C_r	Modal amplitude constant
c_s	Equivalent coefficient of strain rate damping
c_sI	Equivalent damping term due to structural viscoelasticity
Ca	Calcium
CNT	Carbon nanotubes
Cp	Terminal parallel capacitance
Cu	Copper
Ce-NFC	Portland cement-nanocarbon fiber reinforced
D_1, D_2, D_3, D_4	Diodes
D_3	Electrical displacement
d_{31}	Piezoelectric coefficient
D_i	Electric displacement in the i direction

d_{pk}	Piezoelectric constant tensor
D_{Sat}	Saturation electric displacement
DC	Direct current
DNA	Deoxyribonucleic acid
dT/dt	Rate of change of temperature
DTGPS	Deuterated triglycine phosphate-sulfate
DTGS	Deuterated triglycine sulfate
DUT	Device under test
E	Electric field
E_3	Electrical field of generator
E_b	Breakdown voltage
E_k	Electric field in the k direction
EH	Energy harvester
EHDM	Energy harvester with a dynamic magnifier
EI	Bending stiffness
F_D	Detectivity figure of merit
F_I	Current responsivity figure of merit
f_r^{oc}	Frequency at open circuit
f_r^{sc}	Frequency at short circuit
F_V	Voltage responsivity figure of merit
FEA	Finite element analysis
FOM	Figure of merit
FRF	Frequency response function
$GaPO_4$	Gallium orthophosphate
h_s	Thickness of substructure
h_p	Thickness of PVDF
h_{pc}	Distance from the center of the PVDF layer to the neutral axis
I	Equivalent area moment of inertia
I	Imaginary number
I_p	Pyroelectric current
IR	Infrared
k	Spring constant
k_1	Primary oscillator stiffness
k_2	Secondary oscillator stiffness
k_3	Third oscillator stiffness
k_{ij}	Electromechanical coupling coefficient
K_m	Effective bending rigidity of the magnifier beam
K_u	Effective bending rigidity of the entire unimorph beam
$KNbO_3$ICP	Potassium niobate
KS	Knock sensor
L	Effective mass (LPM)
L	Length of the beam

LCR	Inductance, capacitance and resistance meter
$LiNbO_3$	Lithium niobate
$LiTaO_3$	Lithium tantalate
m	Effective mass or mass per unit length of the beam
M	Internal moment of the cantilever
m_1	Primary oscillator mass
m_2	Secondary oscillator mass
m_3	Third oscillator mass
m_t	Tip mass
MAP	Manifold absolute pressure sensor
MEK	Methyl-ethyl-ketone
MEMS	Microelectromechanical systems
MWCNT	Multiwall carbon nanotube
N_u	Constant of the electro-mechanical conversion
Na_2WO_3	Sodium tungstate
NP	Nanoparticles
NPL	Non-piezoelectric layer
NREL	National Renewable Energy Laboratory
p	Pyroelectric coefficient
P	Output power
P_s	Spontaneous polarization
P(VDF-TrFE)	Poly(vinylidene fluoride-trifluoroethylene)
$Pb[Zr_xTi_{1-x}]O_3$	Lead zirconate titanate (PZT)
$PbTiO_3$	Lead titanate (PT)
PCB	Piezoelectric cantilevered beam
PEH	Piezoelectric energy harvesting
PL	Piezoelectric layer
PLT	Lead lanthanum titanate
PLZT	Lead lanthanum zirconate titanate
PMN-PT	Lead magnesium niobate – lead titanate
PT	Lead titanate
PUC	Piezoelectric unimorph cantilever
PV	Photovoltaic
PVA	Poly-vinyl alcohol
PVDF	Polyvinylidene fluoride
PVEH	Piezoelectric vibration energy harvester
PVF	Polyvinyl fluoride
PZT	Lead zirconate titanate
Q	Quality factor
Q	Surface charge
R	Damping coefficient (LPM) or electrical resistance of piezo-patch
R_l	Load resistance

RF	Radio frequency
RMS	Root mean square
S_1	Axial strain
s_{pq}^E	Elastic compliance tensor at constant electric field
S_p	Mechanical strain in the p direction
SHM	Structural health monitoring
Si	Silicon
t	Thickness or plate separation
T_1	Axial stress
T_1	Initial temperature
T_q	Mechanical stress in the q direction
T_{Curie}	Curie temperature
t_D	Short discharge period
tan δ	Loss tangent
TGS	Triglycine sulfate
u_o	Harmonic base displacement
UV	Ultraviolet
V	Voltage
V_{ac}	Amplitude of the peak-to-peak AC small-signal voltage
v_{out}	Amplitude of output voltage
w	Width of the beam
w	Width of the piezoelectric energy harvester
W	Incident power
$w(x,t)$	Transverse deflection of the beam relative to a natural axis
w_b	Base motion
$w_b(x,t)$	Base displacement
$w_{rel}(x,t)$	Transverse displacement relative to the clamped end of the beam
WSN	Wireless sensors network
Y_o	Amplitude of the base translation
YI	Bending stiffness of the composite cross section
Y_p	Young's modulus for PVDF
Y_s	Young's modulus for substructure
ZnO	Zinc oxide
ZnO-NP	Zinc oxide nanoparticles
$\forall$	Area enclosed by the D-E diagram of the hysteresis loop
α_1	Piezo-insert force factor
$\alpha_1 - \alpha_4$	Coefficients determined from the boundaries conditions
δ	Logarithmic decrement
δ_{rs}	Kronecker delta
ΔT_{Curie}	Temperature difference between two-phased transitions
ε	Dielectric constant
ε'	Real part of the dielectric permittivity

ε''	Imaginary part of the dielectric permittivity
ε_{33}^{T}	Permittivity at constant stress
ε_{ik}^{T}	Dielectric constant tensor under constant stress
ε_{o}	Permittivity of free space
ζ	Damping ratio
η_r	Amplitude of the modal coordinate of a clamped-clamped beam
$\eta_r(t)$	Modal coordinate of the clamped–clamped beam for the r^{th} mode
θ	Temperature or electromechanical coupling coefficient
λ_u	Wave number
ρ_p	Mass density of the PVDF
ρ_s	Mass density of the substrate
σ	Constant elastic stress
τ_c	Time constant of the circuit
$\phi_r(x)$	Mass normalized eigenfunction
$\phi_r(x)$	Normal mode of the system
ω	Driving frequency
ω_r	Damped angular frequency
Ω	Ohm