Cambridge University Press 978-1-107-03937-7 — Energy Harvesting Apostolos Georgiadis , Ana Collado , Manos M. Tentzeris Frontmatter <u>More Information</u>

Energy Harvesting

A thorough treatment of energy harvesting technologies, highlighting radio frequency (RF) and hybrid-multiple technology harvesting. The authors explain the principles of solar, thermal, kinetic, and electromagnetic energy harvesting, address design challenges, and describe applications. The volume features an introduction to switched mode power converters and energy storage and summarizes the challenges of different system implementations, from wireless transceivers to backscatter communication systems and ambient backscattering. This practical resource is essential for researchers and graduate students in the field of communications and sensor technology, in addition to practitioners working in these fields.

Apostolos Georgiadis is Honorary Associate Professor at Heriot-Watt University, Edinburgh, UK. He is a former editor-in-chief of *Wireless Power Transfer* (Cambridge). He is an EU Marie Curie Fellow, an URSI Fellow, chair of URSI Commission D Electronics and Photonics, and a distinguished lecturer of the IEEE Council on RFID.

Ana Collado was Assistant Professor at Heriot-Watt University, Edinburgh, UK. She is an EU Marie Curie Fellow.

Manos M. Tentzeris is Ken Byers Professor in Flexible Electronics with the School of Electrical and Computer Engineering (ECE), Georgia Tech. He is a Fellow of IEEE, a Fellow of the Electromagnetics Academy, and a member of URSI Commission D Electronics and Photonics and of the Technical Chamber of Greece.

Cambridge University Press 978-1-107-03937-7 — Energy Harvesting Apostolos Georgiadis , Ana Collado , Manos M. Tentzeris Frontmatter <u>More Information</u>

EuMA High Frequency Technologies Series

Series Editor Peter Russer, Technical University of Munich

Homayoun Nikookar, *Wavelet Radio*Thomas Zwick, Werner Wiesbeck, Jens Timmermann, and Grzegorz Adamiuk (Eds), *Ultra-wideband RF System Engineering*Er-Ping Li and Hong-Son Chu, *Plasmonic Nanoelectronics and Sensing*Luca Roselli (Ed.), *Green RFID Systems*Vesna Crnojević-Bengin (Ed.), *Advances in Multi-band Microstrip Filters*Natalia Nikolova, *Introduction to Microwave Imaging*Karl F. Warnick, Rob Maaskant, Marianna V. Ivashina, David B. Davidson, and Brian D. Jeffs, *Phased Arrays for Radio Astronomy, Remote Sensing, and Satellite Communications*Philippe Ferrari, Rolf Jakoby, Onur Hamza Karabey, Gustavo Rehder, and Holger Maune (Eds), *Reconfigurable Circuits and Technologies for Smart Millimeter-Wave Systems*Apostolos Georgiadis, Ana Collado, and Manos M. Tentzeris, *Energy Harvesting*

Cambridge University Press 978-1-107-03937-7 — Energy Harvesting Apostolos Georgiadis , Ana Collado , Manos M. Tentzeris Frontmatter <u>More Information</u>

Energy Harvesting

Technologies, Systems, and Challenges

APOSTOLOS GEORGIADIS

Heriot-Watt University, Edinburgh

ANA COLLADO Formerly Heriot-Watt University, Edinburgh

MANOS M. TENTZERIS Georgia Institute of Technology



Cambridge University Press 978-1-107-03937-7 — Energy Harvesting Apostolos Georgiadis , Ana Collado , Manos M. Tentzeris Frontmatter <u>More Information</u>



University Printing House, Cambridge CB2 8BS, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

314-321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi - 110025, India

79 Anson Road, #06-04/06, Singapore 079906

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning, and research at the highest international levels of excellence.

www.cambridge.org Information on this title: www.cambridge.org/9781107039377 DOI: 10.1017/9781139600255

© Cambridge University Press 2021

This publication is in copyright. Subject to statutory exception and to the provisions of relevant collective licensing agreements, no reproduction of any part may take place without the written permission of Cambridge University Press.

First published 2021

Printed in the United Kingdom by TJ Books Limited, Padstow Cornwall

A catalogue record for this publication is available from the British Library.

Library of Congress Cataloging-in-Publication Data
Names: Georgiadis, Apostolos, author. | Collado, Ana, author. | Tentzeris, Manos M., author.
Title: Energy harvesting : technologies, systems, and challenges / Apostolos Georgiadis, Ana Collado and Emmanouil M. Tentzeris.
Description: First edition. | Cambridge ; New York, NY : Cambridge University Press, [2020] | Series: EUMA high frequency technologies series | Includes bibliographical references and index.
Identifiers: LCCN 2020023799 (print) | LCCN 2020023800 (ebook) | ISBN 9781107039377 (hardback) | ISBN 9781139600255 (epub)
Subjects: LCSH: Energy harvesting.
Classification: LCC TK2896 .G46 2020 (print) | LCC TK2896 (ebook) | DDC 621.042-dc23
LC record available at https://lccn.loc.gov/2020023799
LC ebook record available at https://lccn.loc.gov/2020023800

ISBN 978-1-107-03937-7 Hardback

Cambridge University Press has no responsibility for the persistence or accuracy of URLs for external or third-party internet websites referred to in this publication and does not guarantee that any content on such websites is, or will remain, accurate or appropriate.

Cambridge University Press 978-1-107-03937-7 — Energy Harvesting Apostolos Georgiadis , Ana Collado , Manos M. Tentzeris Frontmatter <u>More Information</u>

To our daughters Ariadne, Markella-Renata, and Christina-Apostolia

Cambridge University Press 978-1-107-03937-7 — Energy Harvesting Apostolos Georgiadis , Ana Collado , Manos M. Tentzeris Frontmatter <u>More Information</u>

Contents

Preface

| 1 | Introduction | | | |
|---|--------------|--|----|--|
| | 1.1 | Wireless Sensing Platforms | 1 | |
| | 1.2 | Energy Harvesting Revolution | 2 | |
| | 1.3 | This Book | 2 | |
| 2 | 2D-3 | BD Integration for Autonomous Sensors | 5 | |
| | 2.1 | Introduction | 5 | |
| | 2.2 | Inkjet Printing Technology | 7 | |
| | | 2.2.1 Types of Inkjet Printing | 7 | |
| | | 2.2.2 Inkjet Printing Technology as a Fabrication Method | 9 | |
| | | 2.2.3 Inkjet Printing and Surface Energy | 10 | |
| | | 2.2.4 Sintering Process | 11 | |
| | 2.3 | Nanomaterials | 13 | |
| | | 2.3.1 Silver Nanoparticles | 13 | |
| | | 2.3.2 Inkjet-Printable Polymers | 14 | |
| | | 2.3.3 Nanocarbon-Based Materials (Graphene and Carbon | | |
| | | $\mathrm{Nanotubes}-\mathrm{CNTs})$ | 15 | |
| | 2.4 | Nanowire-Based Piezoelectric Nanogenerators | 16 | |
| | 2.5 | Nanotechnology-Based Capacitors | 17 | |
| | 2.6 | Problems and Questions | | |
| 3 | Sola | r (Light) Energy Harvesting | 21 | |
| | 3.1 | Introduction | 21 | |
| | 3.2 | History | 21 | |
| | 3.3 | Light Sources and Measures | | |
| | 3.4 | Efficiency of Solar Cells | | |
| | 3.5 | Ultimate Solar Cell Efficiency | | |
| | 3.6 | Detailed Balance Limit | 26 | |
| | | 3.6.1 Generation of Electron–Hole Pairs Due to Solar Radiation | 27 | |
| | | 3.6.2 Radiative Recombination of Electron–Hole Pairs | 28 | |
| | | 3.6.3 Nonradiative Generation and Recombination of Electron– | | |
| | | Hole Pairs | 29 | |

page xi

| viii | Contents | | | | |
|------|--------------------------------|--|----------|--|--|
| | | | | | |
| | | 3.6.4 The Short-Circuit Current and the Open-Circuit Voltage | 29 | | |
| | 3.7 | Circuit Model of Solar Cells | 30 | | |
| | 3.8 | The Detailed Balance Limit of Maximum Efficiency | 31 | | |
| | 3.9 | Efficiency Limits for Tandem Solar Cells | 35 | | |
| | $3.10 \\ 3.11$ | Solar Antennas and Rectennas Problems and Questions | 38 41 | | |
| 4 | Kinetic Energy Harvesting 44 | | | | |
| | 4.1 | Introduction | 44 | | |
| | 4.2 | Transducer Types | 44 | | |
| | | 4.2.1 Electrostatic Transducers | 45 | | |
| | | 4.2.2 Electromagnetic Transducers | 46 | | |
| | | 4.2.3 Piezoelectric Transducers | 47 | | |
| | 4.3 | Modeling Vibration Energy Harvesting Systems | 47 | | |
| | 4.4 | Vibration Sources | 51 | | |
| | 4.5 | Comparison of Different Kinetic Energy Harvesters | 52 | | |
| | 4.6 | Vibration Energy Harvester Examples | 53 | | |
| | 4.7 | Problems and Questions | 56 | | |
| 5 | Ther | mal Energy Harvesting | 58 | | |
| | 5.1 | Introduction | 58 | | |
| | 5.2 | Thermoelectric Phenomena | 58 | | |
| | | 5.2.1 The Seebeck Effect | 58 | | |
| | | 5.2.2 The Pettler Effect | 59 60 | | |
| | | 5.2.5 The Thomson Effect | 60 60 | | |
| | 53 | Thermoelectric Generators | 60 60 | | |
| | 5.4 | Heat Transfer Fundamentals | 61 | | |
| | 0.4 | 5.4.1 Fourier's Law | 62 | | |
| | | 5.4.2 The First Law of Thermodynamics | 63 | | |
| | | 5.4.3 The Heat Diffusion Equation | 64 | | |
| | 5.5 | TEG Efficiency | 64 | | |
| | | 5.5.1 The Carnot Efficiency | 64 | | |
| | | 5.5.2 Conversion Efficiency Considering Heat Conduction and | | | |
| | | Thermal Losses in the TEG | 65 | | |
| | | 5.5.3 The Figure of Merit | 68 | | |
| | 5.6 | A Thermal and Electrical SPICE Model for the TEG | 69 | | |
| | 5.7 | Thermal Energy Harvester Systems | 70 | | |
| | 5.8 | Problems and Questions | 73 | | |
| 6 | Wireless Power Transmission 77 | | | | |
| | 6.1 | Introduction | 75 | | |
| | 6.2 | Historical Perspective | 77 | | |
| | 6.3 | Near-Field Wireless Power Transmission | 79 | | |

| | | Contents | ix |
|---|-------------------|---|------------|
| | | | |
| | | 6.3.1 Nonresonant Inductive Coupling | 79 |
| | | 6.3.2 Resonant Inductive Coupling | 81 |
| | | 6.3.3 Strong Coupling in Resonant Inductive Coupling Systems | 84 |
| | | 6.3.4 Impedance Matching in Inductive Coupling Systems | 85 |
| | | 6.3.5 Misalignment Effects | 87 |
| | | 6.3.6 Measurements in Inductive Coupling Systems | 89 |
| | 0.4 | 6.3.7 Multiresonator Systems | 93 |
| | 6.4 | Capacitive Power Transfer | 97 |
| | 0.5 6.6 | Far-Field Wireless Power Transmission | 100 |
| | 0.0 | 6.6.1 Time Perersel Duelity | 100 |
| | 67 | Ear Field Wireless Power Transmission at Millimeter Wave | 104 |
| | 0.7 | Fracuencies and Beyond | 107 |
| | 6.8 | Problems and Ouestions | 107 |
| | 0.0 | 1 toblems and Questions | 100 |
| 7 | Elect | romagnetic Energy Harvesting | 110 |
| | 7.1 | Introduction | 110 |
| | 7.2 | Ambient Electromagnetic Energy | 110 |
| | 7.3 | Low-Power Rectifier Circuits | 112 |
| | 7.4 | Nonlinear Optimization of Rectenna Circuits | 120 |
| | 7.5 | Multiband Rectifiers and Rectennas | 124 |
| | 7.6 | Ultrawideband Rectifiers | 125 |
| | 7.7 | Load Resistance and Input Power Effects on Rectifier Efficiency | 129 |
| | 7.8 | Rectification and Angle of Arrival of Incoming Waves | 132 |
| | 7.9 | Signal Optimization for RF Energy Harvesting | 135 |
| | 7.10 | Problems and Questions | 141 |
| 8 | Powe | er Supplies and Storage | 142 |
| | 8.1 | Introduction | 142 |
| | 8.2 | Linear Power Converters | 145 |
| | 8.3 | Switched Mode Power Converters | 147 |
| | | 8.3.1 Steady-State Analysis | 147 |
| | 0.4 | 8.3.2 The Boost Converter | 148 |
| | 8.4 9 E | Summary of Switched Mode Power Converter Properties | 155 |
| | $\frac{8.5}{8.6}$ | Problems and Questions | 158 162 |
| | | - · | |
| 9 | A Sy | Introduction | 163 |
| | 9.1 | Mirology Songing Platforms | 103 169 |
| | 9.4 0.3 | Voltage Conversion Circuits for Energy Hervesting Transducers | 165 |
| | 9.9 Q / | Low-Power Microcontroller Units (MCU) | 167 |
| | 9.4 | Sensor Circuits | 168 |
| | 9.6 | Wireless Transceivers and Backscatter Communication | 169 |
| | 0.0 | | 100 |

| × | Contents | | | |
|---|---------------------|------------------------|-----|--|
| | | | | |
| | 9.7 | Energy Consumption | 172 | |
| | 9.8 | Ambient Backscattering | 173 | |
| | 9.9 | Problems and Questions | 173 | |
| | References Index | | 175 | |
| | | | 194 | |

Cambridge University Press 978-1-107-03937-7 — Energy Harvesting Apostolos Georgiadis , Ana Collado , Manos M. Tentzeris Frontmatter <u>More Information</u>

Preface

This book discusses energy harvesting technologies for low-power wireless sensing platforms. This is a multidisciplinary topic requiring background from different physics-related disciplines such as thermodynamics and mechanics but also electrical engineering, optimization, and signal processing. In addition, material science and additive manufacturing has further helped develop low-cost sensors and circuits that enable form and cost reduction of such platforms and their ubiquitous application.

Our involvement in the field began around 2009. Apostolos and Ana had already been collaborating since 2004 in Spain in the context of a different research field, and around 2009 we decided to begin working on radio frequency (RF) energy harvesting. At this time, we were introduced to Manos during a meeting of the European Union (EU) European Cooperation in Science and Technology (COST) IC0803 project that we were running. From this moment, our collaboration in the field began, and over the last ten years we have produced numerous publications related to different aspects of energy harvesting.

Chapter 1 is an introductory chapter providing a brief overview and a perspective to the research and industrial possibilities related to such a multidisciplinary field of energy harvesting. Chapter 2 is devoted to 2D-3D integration of energy autonomous sensors using inkjet printing fabrication. Chapters 3–5 discuss solar, kinetic and thermal energy harvesting. Chapters 6 and 7 are devoted to wireless power transmission and RF energy harvesting. Chapter 8 discusses dc voltage conversion and power storage, and finally, Chapter 9 is devoted to a system overview of wireless sensing platforms with energy harvesting capability. As part of a course, one could begin with Chapter 1, follow with Chapter 2, and then cover the chapters related to the different energy harvesting technologies. Chapters 3 through 5 and the combined set of Chapters 6 and 7 could be taught in any order. Chapter 2 may also be offered after Chapters 3 through 7. One could then cover the final Chapters 8 and 9.

We would like to thank our numerous former students who have contributed to our work on energy harvesting. First and foremost, Sangkil Kim, now assistant professor at Pusan National University, South Korea, has contributed to a great number of publications and provided the main draft of Chapter 2 based on his expertise in inkjet printing. Special thanks go to Dr. Spyros Daskalakis, Heriot-Watt University, for his help with the book editing. Our thanks also go

Cambridge University Press 978-1-107-03937-7 — Energy Harvesting Apostolos Georgiadis , Ana Collado , Manos M. Tentzeris Frontmatter <u>More Information</u>

xii Preface

to our former students, collaborating students and visiting students, Francesco Giuppi, Huawei, Milan; Kyriaki Niotaki, Maynooth University; Gianfranco Andia Vera, Multiwave; Rushi Vyas, University of Calgary; John Kimionis, Nokia Bell Labs, New Jersey; Alirio Boaventura, Daniel Belo, Ludimar Guenda and Ricardo Fernandes from the University of Aveiro; Marco Virili, Qorvo, Inc.; Valentina Palazzi, University of Perugia; Massimo del Prete, University of Bologna; Chiara Mariotti, Infineon Technologies; Maria Valeria de Paolis, Laboratory for Analysis and Architecture of Systems (LAAS) of the French National Center for Scientific Research (CNRS); Martin Schuetz, University of Erlangen–Nuremberg; Ferran Bolos, Javier Blanco, Angel Servent, Ernest Silvestre, Ricard Martinez, Omar Andre Campana Escala, Cesar Meneses Ghiglino, and Gustavo Adolfo Sotelo Bazan from the Polytechnic University of Catalunya, Castelldefels; and Sergi Rima from Rovira i Virgili University. We apologize for potential errors in affiliations; there are just too many of you to accurately keep track!

We would also like to thank our numerous collaborators: Professor Nuno Borges Carvalho, Aveiro University; Professor Luca Roselli, University of Perugia; Professor Yoshihiro Kawahara, University of Tokyo; Professor Alessandra Constanzo, University of Bologna; Professors Lauri Sydanheimo, Leena Ukkonen, and Toni Bjorninen, Tampere University; Professor Zoya Popovic, University of Colorado, Boulder; Professor John Sahalos, University of Nicosia; Professor Smail Tedjini, Grenoble Institute of Technology; Professor Hendrik Rogier, Ghent University; Professors Luciano Tarriconne and Giuseppina Monti, University of Salento; Professors Antonio Lazaro and David Girbau from Rovira i Virgili University; and Professor George Goussetis, Heriot-Watt University. We for your collaboration and fruitful discussions throughout this period but foremost for your friendship.

Finally, we would like to express our gratitude to Julie Lancashire from Cambridge University Press for her continuous support and patience as well as to Sarah Strange and the rest of the editorial staff at Cambridge University Press.

We hope that the book can provide a starting point for our readers to the world of energy harvesting, and we welcome any comments and feedback!