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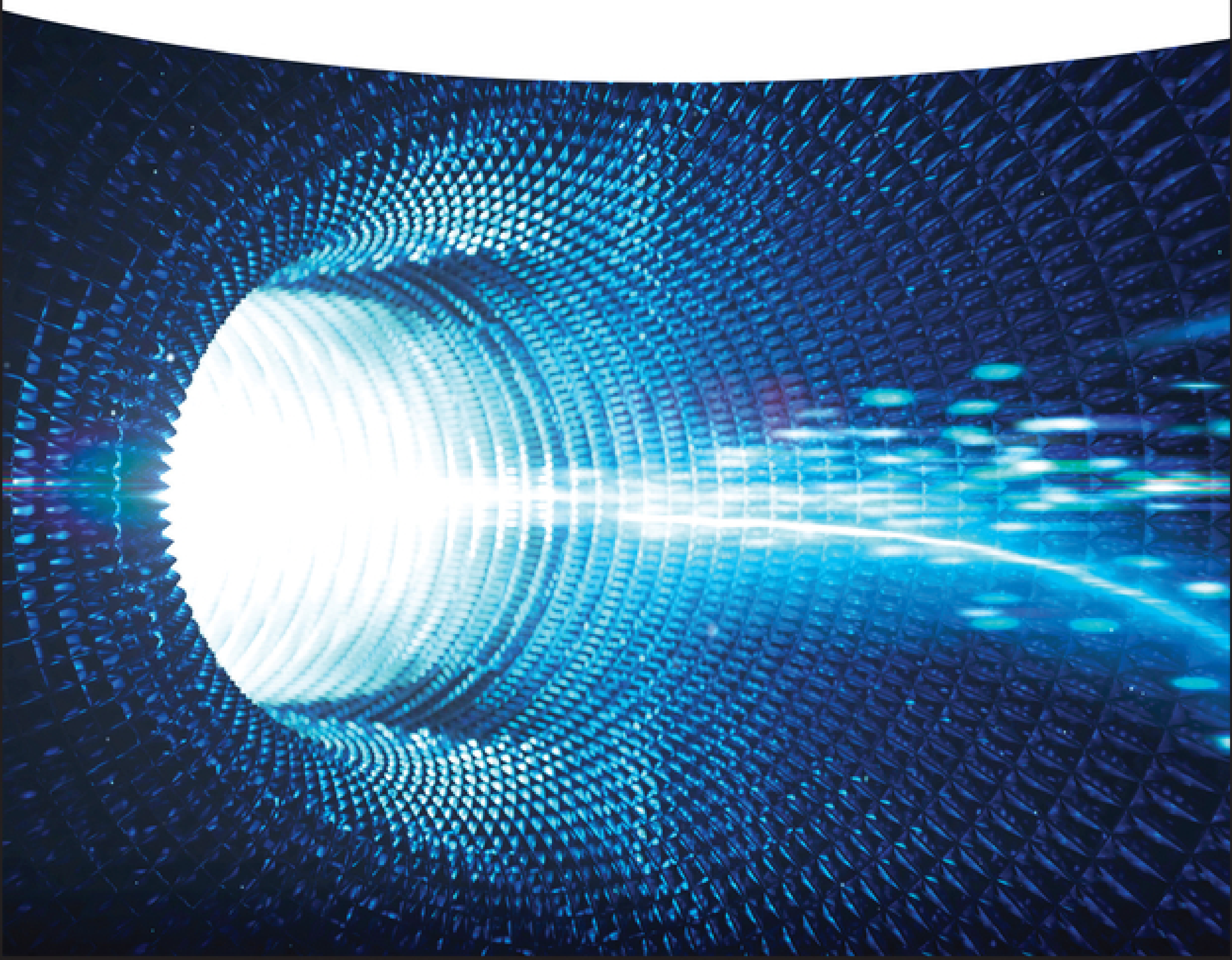

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Contents

Preface

With the rapid development of Artificial Intelligent Internet of Things (AIoT) technologies based on a large number of wireless sensing nodes, battery is becoming the main limitation of sensor node power supply due to its limited service life, difficult maintenance, environmental pollution, and potential security risks. Piezoelectric energy-harvesting technology, an old but promising technology, is being developed as a replacement of the battery in many areas so that one can obtain a sustainable power supply. However, the frequency of most ambient vibration sources is very low (less than 200 Hz) compared to most traditional silicon-based microelectromechanical systems. High structural stiffness of piezoelectric energy harvesters makes it difficult to obtain effective and stable output at low frequency. At the same time, there is an increasing demand for flexible piezoelectric energy-harvesting and energy-sensing technologies with the emergence of flexible electronics technology due to their high compatibility with some extreme or complex objects. At present, flexible piezoelectric energy-harvesting and energy-sensing technologies are being used in new ones for powering wearable or implantable electronics. This book addresses the design methods, flexible piezoelectric materials, different working mechanisms, micromachining processes, and the application of flexible energy harvesters for wearable and implantable devices.

In particular, cutaneous activities mainly derived from motion in limbs, pulse waves in arteries, or disturbances associated with breathing are studied. The subtle changes caused by cutaneous activities can be measured via the sensors attached to the skin, which is valuable for in situ monitoring of vital signs in healthcare and recognizing different gestures in man–machine interaction. Conventional sensors face some critical demerits, such as rigid structures and high power consumption, which cause inconvenience in daily life for medical applications. These sensors detect physiological signals produced by human activities, but the power supply is critical for their operation, which limits their wearable or implantable application. Therefore, some flexible sensors should be reviewed again and summarized in detail for wearable and implantable applications.

To address researchers, scientists, and application engineers from different backgrounds, this book systematically and comprehensively demonstrates the global progress and achievements in the field of flexible piezoelectric energy-harvesting and energy-sensing technologies. This book covers the fundamentals, developments, discussions in the design and fabrication of energy-harvesting, energy-sensing, and their corresponding applications. The working principle of piezoelectric devices is introduced in Chapter 1. The requirement of flexible energy harvesters and sensors is demonstrated. Chapters 2 and 3 report the design methods and fabrication processes of flexible energy-harvesting techniques. Low-frequency cantilever-based energy harvesters, and free- and forced-vibration nonlinear energy harvesters are introduced in Chapters 4–6. Chapter 7 demonstrates water vortex shedding-induced and aeroacoustics-driven jet-stream wind-energy harvesters. Some examples of wearable and implantable applications are described in Chapters 8 and 9. The working principle and its application for body sensor network are covered in Chapter 10. In Chapter 11, we introduce the approaches for sensing data from the flexible sensor to the fullest with the assistance of machine-learning algorithms. The existing challenges of current intelligent systems and future trends are provided, which give a glimpse of further developments in the 5G/internet of things (IoT) era.

The book can be an introduction for undergraduates, graduates, and developers who are working in this area. This book will bring some new ideas for some researchers and engineers in the flexible energy-harvesting and energy-sensing fields.

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01 October 2021 *Bin Yang*

Foreword

Piezoelectric energy-harvesting and energy-sensing technologies are not new. The dilemma of rapidly developing piezoelectric energy harvesters or sensors is that the performance is contradictory to the structural flexibility. To make a contribution that would obtain a trade-off for this contradiction, we provide a framework for the recent advances and also show a blueprint from fundamental structural design to the practical fabrication and from standalone devices to the integrated systems for promoting their practical applications. To achieve this goal, we needed to cooperate closely with every editor, and we also needed to convince leading scientists to take time from their busy schedules to provide comments for every chapter. Fortunately, nearly all those we approached were very friendly. Many constructive suggestions have been accepted for improving this book. What you hold in your hand is the culmination of our wisdom, although not comprehensive. We are extremely grateful to all of our contributors.

One striking feature of this book is that more than one-third of the chapters focus on discussing the practical applications, and even some challenge issues resulting from battery have been tried to solve based on some ingenious batteryless strategies. It has been alleged that the best science is done in academia. This book may provide an uncommon insight for scientific exploration. The main reason may be that many of the piezoelectric energy-harvesting or energy-sensing techniques involved require expensive equipment and infrastructure as well as large collaborations between scientists from disparate disciplines, especially further study in practical applications.

Although tremendous progress has now pervaded laboratories across the world, the ultimate success of any energy-harvesting or energy-sensing technology is measured in the quantity and quality of energy conversion efficiency or sensing sensitivity that it produces. Flexible piezoelectric energy harvesting or sensing has only been practical for the past decade, too soon to expect it to produce marketed electronic devices, but we believe these will come in time. Moreover, many of the techniques and concepts described in this book will improve the flexible piezoelectric energy-harvesting or energy-sensing technologies in subtle, tangential ways. Ideally, readers will be endowed to improve the methods described here, or even to develop fundamentally new methods for flexible piezoelectric energy harvesters or sensors.

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Finally, we would like to thank all colleagues and members who greatly contributed in writing several chapters: Lijun Lu, Yang Huang, and Guosheng Hu at Shanghai Jiao Tong University, Zixuan Zhang at the National University of Singapore. Also, we thank the Wiley-VCH editorial team for giving us a great opportunity to edit this book.

1

Introduction

1.1 Background

With the rapid development of information technology, microelectronics technology has been widely used in people's daily life, such as healthcare monitoring, intelligent communications, cloud computing, big data, and Internet of Things, and has made considerable progress in intelligent information technology. However, as the current microelectronic devices mainly rely on the wired power supply or battery power supply, wired power supply greatly limits the portability of microelectronic devices and the freedom of space applications, whereas the battery power supply is unsustainable and there are certain safety and environmental pollution problems. In particular, artificial intelligence, the Internet of Things, 5G high-velocity communications, wearable and implantable electronic devices or microsystems, and other new generations of information technology are emerging and rapidly developing. A large number of distributed microsensors composed of wireless sensor networks (WSNs) is essential for these emerging technologies, which makes the problem increasingly prominent. Traditional battery power supply strategies have become a major factor limiting their progress toward miniaturization and flexibility [1]. Therefore, it is observed that the opportunities for batteryless technologies by harvesting surrounding energy of the powered objects or passive sensors are coming, and they are urgent requirements for maintaining the sustainable development of the emerging technologies.

Energy harvesting is the conversion of surrounding waste or useless kinetic, radiant, thermal, and biological energy into electrical energy (as shown in Figure 1.1), and is new energy enabling technology for wireless sensor network node applications. Kinetic energy is the energy that an object has due to its movement, such as mechanical vibrations, human movement, structure rotation, water flow, and so forth, which is ubiquitous in the environment. In contrast to any other energies in surroundings, kinetic energy is widely distributed, clean and safe, easy to miniaturize and integrate, and has a low environmental impact, making it the main source of energy for research into energy-harvesting technologies. With the rapid development of microelectronics technology, more and more low-power consumption microelectronic devices have emerged, while the rapid progress of

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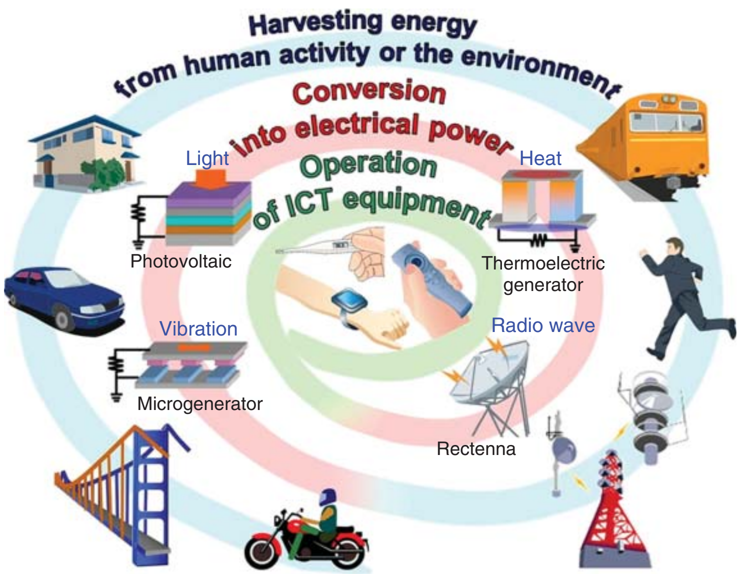

Figure 1.1 Schematic illustration of energy-harvesting strategies based on the ambient energies [2]. Source: Reprinted with permission from Fujitsu Laboratories Ltd. [2]; © 2016 MEMS consulting.

kinetic-energy-harvesting technology in terms of material preparation, conversion methods, device structures, and energy-management circuits has obtained higher and higher conversion efficiency, and the generated electricity has gradually been able to meet the power supply needs of many microelectronic devices, gradually ushering in the development opportunities of batteryless microelectronic systems. Therefore, the research of kinetic-energy-harvesting technology is expected to completely get rid of the shackles of wired power supply and battery supply, and realize batteryless power supply in complex scenarios as well as in situ self-supply of wireless sensor network nodes in the Internet of Things, so as to achieve wireless batteryless sustainable power supply, thus solving the problems of system non-portability, high maintenance costs, environmental pollution, limited life span, and related safety hazards caused by power supply wires or batteries. It is also free from the constraints of battery power supply on the development of flexible and miniaturized electronic devices.

Flexible piezoelectric sensor is one of self-powered sensors, generally be delivered into two types – one is passive sensors, such as piezoelectric sensors, electromagnetic sensors, and thermoelectric sensors; the other one is active sensors with an energy harvester to provide power supply for themself. In this book, it is to avoid the misunderstanding that we described the former as self-power devices and the latter as batteryless devices. Self-powered sensors as passive devices can work almost without power consumption for sensing, which is significant for long-term working and energy saving. In this book, we focus on flexible piezoelectric energy harvesting and expand some corresponding technologies to discuss the development of flexible piezoelectric tactile sensors and their applications in Internet of Things, healthcare monitoring, intelligent recognitions, and some other interesting and possible applications combing with the artificial intelligent technologies.

1.2 Working Principle of Piezoelectric Devices

Piezoelectric energy harvesting or sensing technique is mainly based on the positive piezoelectric effect of materials, which was discovered by the Curie brothers in 1880 in alpha-quartz crystals and reflects the coupling between the elastic and dielectric properties of crystals, meaning that there is no electric field but only the strain or stress generated by the action of an external force, resulting in the generation of electrodes in the crystal, leading to the appearance of a different macroscopic charge on certain surfaces or inside the medium. These macroscopic charges are called polarized charges and cannot leave the dielectric or move freely within the dielectric, so they are also called bound charges [3]. Researches into piezoelectric energy harvesting or sensing technique began at the end of the last century and the main transformation methods include the free vibration method and the forced vibration method, which all rely on mechanical surrounding excitations, such as mechanical vibration and dynamic force. Therefore, piezoelectric effect has been widely investigated for force or stress sensing and energy harvesting.

In terms of mechanical energy harvesting, piezoelectric energy harvesting is one of major components, mainly including piezoelectric, electromagnetic, electrostatic, triboelectric, flexoelectric, and electrochemical mechanisms.

Electromagnetic-energy-harvesting technology is based on Faraday's law of electromagnetic induction, using a part of the conductor of a closed circuit to make a motion of cutting magnetic induction lines in a magnetic field, causing a change in magnetic flux, forming an induced electric potential, and generating an induced current in the conductor. The main transformation methods are cantilever beam, suspension bridge, single-track-reciprocating vibration and rotary motion [4, 5]. Electrostatic-energy-harvesting techniques are used to create a circuit current by forcing a change in charge or voltage between the two plates of a capacitor through mechanical motion [6]. The main structure of an electrostatic energy harvester is a capacitive structure consisting of two conductive electrodes separated by air or dielectric and an elastic structure connected by the electrodes. The basic working principle of triboelectric-energy-harvesting technology consists mainly of contact initiation and electrostatic induction [7]. According to the charge-separation mechanism, the harvesting forms of triboelectric electrical energy harvesters can be divided into contact based on vertical charge polarization and sliding based on in-plane charge polarization. Electrochemically driven method [8] is a new type of kinetic-energy-harvesting method. Electrochemically driven energy harvesters are mainly based on the migration of ions in the composition of electrochemically active materials (e.g. alloys of Li and Si or Ge) subjected to external stresses, resulting in an electrical potential difference. The flexoelectric effect is similar to the piezoelectric effect and refers to the polarization of a dielectric material when it is bent by an

Table 1.1 Advantages and disadvantages of the different kinetic energy harvesters.

Working principles	Advantages	Disadvantages
Piezoelectric	No requirement for external energy at starting, high energy density, simple structure, and easy integration.	Easy self-discharge at low frequencies, high dependence on materials, high output impedance, and difficult flexibility.
Electromagnetic	No mechanical contact is required, low mechanical damping, high reliability, high output current, and low output impedance.	Difficult to miniaturize, low efficiency at low frequencies, low output voltage, and difficult integration.
Electrostatic	MEMS process compatibility, suitable for low frequencies, easy integration, and high electrical damping.	Dielectric breakdown, requirement of external energy at starting, complex fabrication process, high output impedance, low current, and easy to fail due to pull in instability.
Triboelectric	Good flexibility, simple structure, and high output voltage.	Low output current, dependence on friction surfaces, low reliability, susceptible to environmental humidity, difficult to miniaturize, high impedance.
Electrochemical	Flexibility and low frequency.	Low output voltage.
Flexoelectric	High-quality factor and easy integration.	Weak effect for bulk material and low output energy.

external force, resulting in structural deformation when an external electric field is applied. It is a weak effect for bulk materials [9], and therefore studies of flexural electricity are usually focused on the nanoscale.

Table 1.1 lists the advantages and disadvantages of the different mechanisms of kinetic-energy-harvesting methods. From the table, it can be found that electromagnetic and triboelectric methods are difficult to miniaturize due to their mechanism of action, and electromagnetic-energy-harvesting methods are difficult to be compatible with flexible electronic devices; triboelectric-energy-harvesting methods are not yet able to break through the limitation on material triboelectric surface loss; electrostatic methods are highly dependent on the level of process integration and manufacturing, and are prone to microscale adsorption failure problems; electrochemical drive methods and flexoelectric methods are too inefficient in terms of output. It is still difficult to meet the power supply needs of low-power microelectronic devices. In contrast, piezoelectric-energy-harvesting methods have been widely studied for their high energy density, simple structure, easy integration, and no need for external energy to start, but they also suffer from high-frequency dependence, limited piezoelectric material properties, flexibility difficulties, and high output impedance. The flexible piezoelectric-energy-harvesting technology based on mechanical thinning process is expected to solve the problems faced in the development of flexible piezoelectric energy harvesters.

1.3 Requirement for Flexible PEH

The application conditions of piezoelectric-energy-harvesting technology are very demanding. On the one hand, it requires sufficient mechanical energy available in the working environment, and on the other hand, it requires the device to provide sufficient electrical energy under the premise of ensuring applicability and safety, so the working environment of the device and the power consumption of the equipment to be powered become the main limiting factors for the expansion of the application field of piezoelectric-energy-harvesting technology, which is also the main hot spot of the current applied research.

In terms of common microelectronic devices, the application of energy-harvesting technologies is mainly to consider some specific environments where wired power supply is inconvenient and battery power supply is a safety hazard due to the lifetime problem, and the realization of batteryless devices can effectively get rid of these problems. At present, the batteryless research of low-power electronic devices mainly includes some implantable medical devices with low power consumption (as shown in Figure 1.2) and pressure monitoring systems (as shown in Figure 1.3).

As for rapidly developing Internet of Things, it refers to various devices and technologies, such as various information sensors, radio-frequency identification technology, global positioning system, infrared sensors, laser scanners, to collect any object or process that needs to be monitored, connected, and interacted with in real time, collecting its sound, light, heat, electricity, mechanics, chemistry, biology, location, and various other needed information, and through various possible network access, realize the ubiquitous connection between things and things, things and people, and realize the intelligent sensing, identification and management of objects and processes. The Internet of Things is an information carrier based on

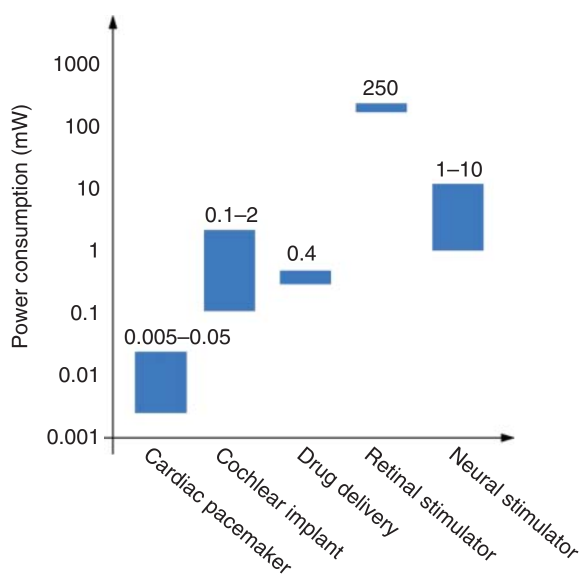

Figure 1.2 Power consumption of different medical and implantable devices [10, 11]. Source: Data from Yang et al. [10].

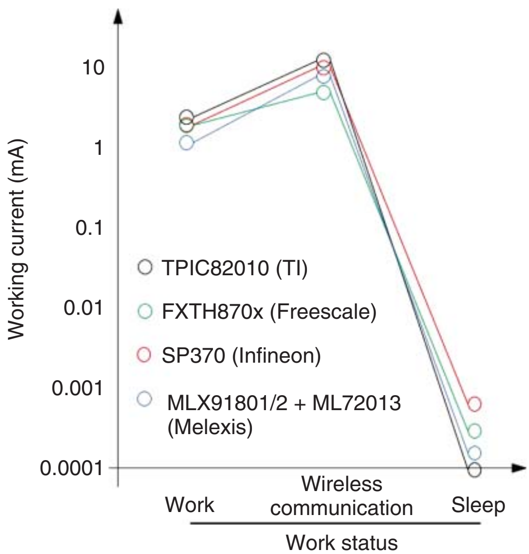

Figure 1.3 The main IC solutions of the tire pressure monitoring system on Market [10]. Source: Data from Yang et al. [10].

the Internet and traditional telecommunication networks, which allows all common physical objects that can be independently addressed to form an interconnected network. Combined with Artificial Intelligent (AI) technology and the new generation of high-speed communication technology (5G or 6G) to achieve high-speed processing of sensory information, high-speed interaction, to achieve timely sensing and timely decision-making of the artificial intelligence & Internet of Things (AIoT) system.

The current power consumption of most IoT devices is shown in Figure 1.4. When using these devices to achieve the interconnection and interoperability of everything, such a huge power supply network is also needed behind the huge connectivity network. Given that wired power supply will greatly limit the scope of its spatial application, the current reliance on battery-powered wireless sensing network technology, however, will certainly cause a large amount of battery consumption and high maintenance costs due to battery life, so the development of the Internet of Things urgently needs a convenient and sustainable power supply network.

With the development of energy-harvesting technology and low-power IoT devices, the environmental energy that can be converted by energy harvesters also gradually meets the power supply needs of some IoT devices, and in the future, with the further development of both, it is very promising to achieve sustainable power supply for IoT. Figure 1.5 shows the power density and output voltage range statistics of common energy-harvesting methods and lithium-ion battery technology. In terms of mechanical kinetic energy harvesting, piezoelectric-energy-harvesting technology can achieve greater energy density and output voltage compared to electromagnetic-energy-harvesting technology and has the potential to be a greater alternative to lithium batteries.

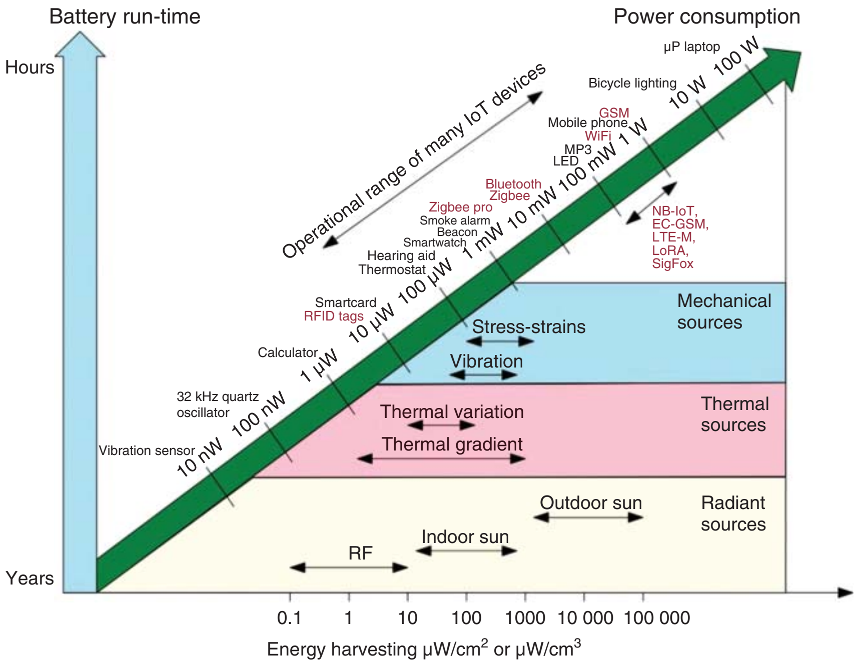

Figure 1.4 Power consumption for various applications of IoT and power densities for various energy sources. Source: Shirvanimoghaddam et al. [12] / CC BY-SA 4.0.

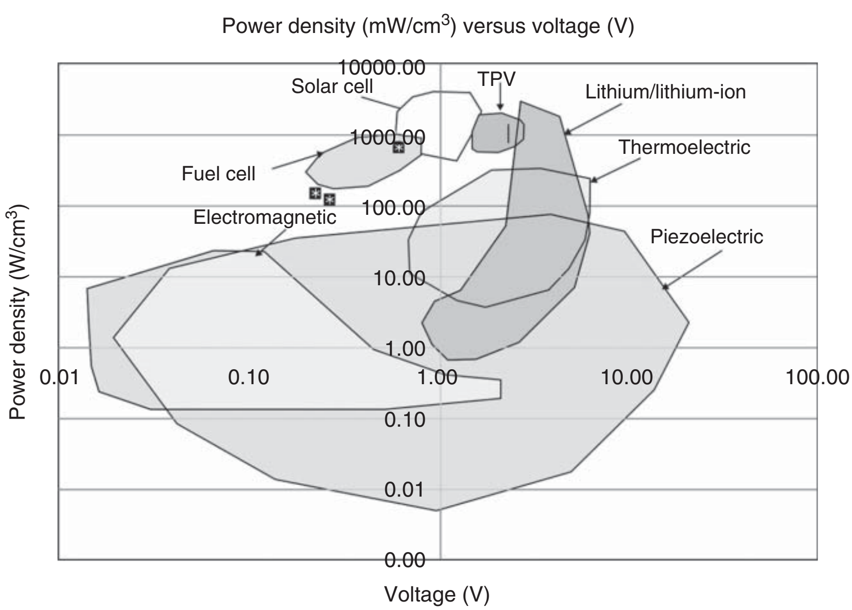

Figure 1.5 Power density versus voltage comparison of common regenerative and lithium/lithium-ion power supply strategies. Source: Cook-Chennault et al. [13] / with permission of IOP Publishing.

1.4 Requirement for Flexible Piezoelectric Sensors

For decades, miniaturization of electronics and advances in materials are paving the way for prosperous development of wearable and implantable devices. Human is experiencing the great conveniences that are brought by diverse electronics, including smartwatch, glasses, shoes, glove, pacemaker, and necklace. With the aid of 5G communication, artificial intelligence, and edge computing, the highly digitized human will undergo a seamless involvement in the whole network or internet of things. Some of them possess the functions of the mobile console for processing and displaying the data. Meanwhile, various sensors with physical, optical, or chemical mechanisms, form another major group in wearable or implantable systems. Hence, our physical activities, vital sign, and physio-biochemical indicators can be continuously monitored for health inspection or performing manipulations, besides, the environmental variations are also able to be detected for further utilization. However, the current commercialized wearable and implantable devices usually rely on the battery-based power supply, such as piezoresistive, optical, and capacitive sensors, and various actuators, which are inevitably encountered with some constraints, including the long-term sustainability and the further shrinkage of device size. As a solution to this urgent power issue, a flexible piezo-microelectromechanical system (piezo-MEMS)-integration strategy was presented on base of piezoelectric thick film with good piezoelectric properties. The sensors based on piezoelectric effect attract broad attention due to their intrinsic high dynamic response and high fidelity [14–19], especially ultra-low power consumption.

In this book, we intend to discuss piezoelectric energy harvesters (PEHs) and piezoelectric sensors on account of the piezo-MEMS thick-film process. The discussion starts with fabrication of piezo-MEMS thick film, design of piezoelectric devices, and some methods of theoretical analysis. Then, we firstly introduce the usual investigations, including common linear-mechanism cantilever piezoelectric energy harvester based on the piezoelectric thick film and nonlinear-mechanism PEHs, to discuss the design and fabrication of the PEHs. Thereafter, we introduce the rotation-driven flexible PEH, the aeroacoustics-driven jet-stream wind energy harvester, and the wearable and implantable PEHs in different chapters, respectively. Finally, we focused on the piezoelectric tactile sensors and advances in artificial-intelligence-assisted flexible sensors.

1.5 Summary

In this book, we focused on introducing the recent advances and important development in flexible piezoelectric energy harvesting and sensing techniques, mainly including the design, fabrication, theoretical analysis, nonlinear mechanism induced bandwidth properties, and some applications in self-powered systems of flexible piezoelectric energy harvesters, and we also introduced the key role of flexible piezoelectric devices in the field of wearable electronics and tactile sensing.

We also provided some introduction about the emerging research directions due to disciplines-crossing, such as artificial intelligence technology-assisted design optimization, data processing, or sensing recognition.

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2

Design of Flexible Piezoelectric Energy Harvesters

2.1 Introduction

Design of piezoelectric energy harvesters is to generate highly effective strain in piezoelectric layer. The piezoelectric energy harvesters mainly include the free-vibration type based on the inertia principle and the forced-vibration type based on the action of periodic external forces. For a piezoelectric material with defined piezoelectric properties, how to achieve the most effective strain generation by piezoelectric crystals through the structural design of piezoelectric energy harvesters becomes the key to achieving high-conversion efficiency of piezoelectric energy harvesters.

The cantilever beam structure can produce higher average strain for a given force condition and has greater conversion efficiency for application in energy harvesters. It is also simple in structure and thus has received a lot of attention from researchers. At present, most of the studies on cantilever beam vibration energy harvesters focus on the uniform cross-sectional beam structure composed of piezoelectric and nonpiezoelectric layers with the same length, and the output power of the cantilever beam vibration energy harvester is greatly affected by different piezoelectric layer arrangement lengths, but there are relatively few relevant research reports, and there is a lack of systematic theoretical analysis for this nonuniformly distributed cantilever beam study, especially for the commonly used. The performance of the cantilever beam vibration energy harvester with mass bulk is not clear.

In this chapter, we discuss some challenges of flexible piezoelectric energy harvesters in structural design, types of generally used structural designs, methods of theoretical analysis, methods of simulation, and the corresponding experimental verification. Finally, we introduce how to optimize the structural designs by using the data-driven strategy.

2.2 Challenges of Structural Design

2.2.1 Low Frequency

It is important that the resonant frequency of the piezoelectric energy harvester can meet the requirement of matching the frequency of the vibration source in the

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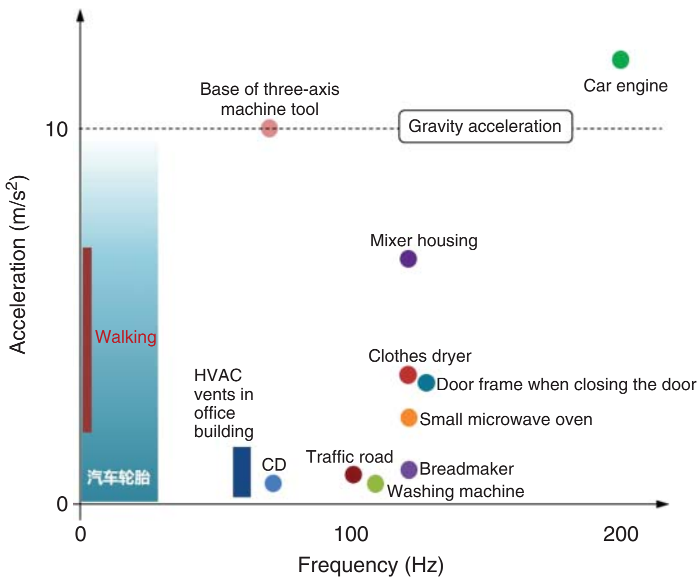

Figure 2.1 Frequency and acceleration levels of various ambient vibration resources. Source: Adapted from [1, 2].

operating environment to achieve the best operating condition of the device. Given that the frequency of common environmental vibration sources is usually less than 200 Hz (Figure 2.1), the development of high-performance piezoelectric energy harvesters with low frequencies has attracted extensive attention and research from scientists.

The research of vibration energy harvesters is based on the environmental state of the harvesting device, and the optimal operating frequency required for the device varies according to its working environment. To achieve high-efficiency energy harvesting, it is necessary to control the resonant frequency of the device in line with the environmental vibration frequency to achieve resonance, and microelectromechanical systems (MEMS) vibration energy harvesters are difficult to control the resonant frequency in the low-frequency range below 200 Hz due to their inherent small size and process-compatible materials, which make most MEMS vibration energy harvesters have poor output performance under actual operating conditions. Therefore, the development of low-frequency MEMS vibration energy harvesters is particularly important to advance their applications in real-world environmental conditions.

The basic composition of the cantilever beam free-vibration energy harvester mainly consists of a piezoelectric layer, a substrate layer, and a mass bulk, whose intrinsic frequency can be expressed as [3]:

$$f \propto \sqrt{\frac{\mathrm{EI}}{mL^4}} \tag{2.1}$$

where EI is the flexural stiffness of the cantilever beam, m is the equivalent mass of the cantilever beam, and L is the total length of the cantilever beam. It can be seen that the inherent frequency is mainly controlled by the flexural stiffness of the cantilever beam structure, the cantilever beam mass distribution, and the total length of the cantilever beam. For the MEMS cantilever beam energy harvester, due to its small-size limitation, its effective length cannot be too large, and adding end-mass bulks to adjust the mass distribution of the cantilever beam structure is an effective way to reduce the intrinsic frequency. However, the conventional piezoelectric energy harvester with high-modulus silicon material as substrate is not only difficult to achieve the design requirements of low frequency, but also easy to be damaged under higher excitation acceleration conditions, and the device is difficult to ensure normal operation under the effect of complex environment. At the same time, the size of the mass bulk is also limited by considering the limitation of process and structure size, so the frequency regulation by adjusting the mass bulk alone has great limitation. The magnitude of flexural stiffness, besides being limited by the cross-sectional dimensions, also depends mainly on Young's modulus of the material used in the cantilever beam itself. The conventional MEMS cantilever beam energy harvester is mainly based on silicon as the substrate material, which has a high Young's modulus and is prone to brittle cracking. Therefore, the current research on low-frequency piezoelectric free-vibration energy harvesters is mainly focused on mass bulk bonding and low-stiffness beams.

On the other hand, the study of the energy-harvesting method of forced vibration based on the ambient vibration method and the consideration of the device size allow the combination of the design of the boosting mechanism to raise the ultralow-frequency-forced vibration to a higher frequency range, thus improving the energy conversion efficiency.

2.2.2 Bandwidth

Usually, the cantilever beam vibration energy harvester only shows high-output performance in a small range near the resonant frequency point, and its output performance decreases very significantly when it deviates from its resonant frequency. Therefore, to solve the problem of single-frequency response of vibration energy harvester, there are two main solutions – array-type cantilever beam topology and flexural bridge-type nonlinear vibration topology.

Array cantilever beam topology is the result of integrating multiple cantilever beam vibration energy harvesters with different resonant frequencies to achieve multifrequency response (Figure 2.2a), and connecting these devices in series or parallel to achieve high-electromechanical-conversion efficiency at multiple frequency points or certain frequency bands (as shown in Figure 2.2b) to meet the needs of different vibration environments.

Bridge-type structures are less frequently used in the study of energy harvesters because of their large resonant frequencies and low strain. However, the resonant frequency and output performance of energy harvesters based on flexible substrates can be improved, and nonlinear vibration effects can be achieved by applying certain bending stress in advance or by using the bending curvature of the structure itself in