

## Contents

<b>Preface</b>	<i>ix</i>
<b>Foreword</b>	<i>xi</i>
<b>Acknowledgments</b>	<i>xiii</i>
<b>1</b>	<b>Introduction</b> <i>1</i>
1.1	Background <i>1</i>
1.2	Working Principle of Piezoelectric Devices <i>3</i>
1.3	Requirement for Flexible PEH <i>5</i>
1.4	Requirement for Flexible Piezoelectric Sensors <i>8</i>
1.5	Summary <i>8</i>
	References <i>9</i>
<b>2</b>	<b>Design of Flexible Piezoelectric Energy Harvesters</b> <i>11</i>
2.1	Introduction <i>11</i>
2.2	Challenges of Structural Design <i>11</i>
2.2.1	Low Frequency <i>11</i>
2.2.2	Bandwidth <i>13</i>
2.2.3	Flexibility <i>15</i>
2.3	Types of Structural Design <i>17</i>
2.3.1	Cantilever Beam Structure <i>19</i>
2.3.2	Diaphragm Type <i>19</i>
2.3.3	Bridge Type <i>19</i>
2.3.4	Buckling Type <i>20</i>
2.3.5	Piezoelectric Stack- and Cymbal-Type Piezoelectric Energy Harvester <i>21</i>
2.4	Theoretical Analysis <i>21</i>
2.4.1	Electromechanical Coupling Analysis <i>25</i>
2.4.2	Electrical Output Analysis of the PEHs <i>31</i>
2.4.3	Output Performance of the PEHs <i>34</i>
2.5	Finite Element Analysis <i>36</i>
2.5.1	Output Performance of the PEHs <i>36</i>
2.5.1.1	Effect of Piezoelectric Layer Length on Cantilever Beam Energy Harvesting <i>36</i>

2.5.1.2	Effect of Piezoelectric Layer Thickness on Cantilever Beam Energy Harvesting	39
2.5.1.3	Effect of Cantilever Beam Width on Cantilever Beam Energy Harvesting	40
2.5.1.4	Effect of Cantilever Beam Length on Cantilever Beam Energy Harvesting	41
2.5.1.5	Effect of Mass Bulk on Energy Harvesting From Cantilever Beam	42
2.5.1.6	Effect of Different Substrate Materials on the Performance of Composite Layer-Based Cantilever Beam Piezoelectric Energy Harvesters	43
2.5.1.7	Effect of Excitation Intensity on the Performance of a Flexible Substrate Cantilever Beam Piezoelectric Energy Harvester	44
2.5.2	Structural Strain Distribution Analysis	45
2.6	Experimental Verification	46
2.6.1	Fabrication of the Cantilever PEH	46
2.6.2	Measurements	46
2.6.3	Results and Discussions	46
2.7	Data-Driven Further Optimization	50
2.7.1	Methods	51
2.7.2	Results and Discussion	54
2.8	Summary	54
	References	56

### **3 Fabrication of Flexible Piezoelectric Energy Harvesters 63**

3.1	Introduction	63
3.2	Piezoelectric Ceramic Thin Film	65
3.3	Piezoelectric Ceramic Thick Film	68
3.4	Spinning-Coated PVDF Film	72
3.5	Electrospinning Piezoelectric Film	74
3.6	Summary	77
	References	77

### **4 Cantilever Piezoelectric Energy Harvesters 83**

4.1	Introduction	83
4.2	Optimized Cantilever PEH	84
4.2.1	Structure Design and Fabrication	85
4.2.2	Output Performance	86
4.3	Bimorph PEH	89
4.3.1	Structure Design and Fabrication	89
4.3.2	Output Performance	93
4.4	Optimized Bimorph PEH	98
4.4.1	Structure Design and Fabrication	99
4.4.2	Output Performance	100
4.4.2.1	Comparative Analysis of Normalized Power Density	101
4.5	Summary	103
	References	103

<b>5</b>	<b>Free-Vibration Nonlinear Piezoelectric Energy Harvesters</b>	<b>107</b>
5.1	Introduction	107
5.2	Free-Vibration Nonlinear Mechanism	108
5.2.1	Theoretical Analysis	108
5.2.2	Energy Equation	110
5.2.3	Finite Element Analysis	119
5.3	Design Method for Custom Nonlinear Characteristics	123
5.4	Flexible Buckled-Bridge PEH	125
5.5	Flexible Buckled-Bridges-Stacked PEH	128
5.6	Summary	130
	References	130
<b>6</b>	<b>Forced-Vibration Nonlinear Piezoelectric Energy Harvesters</b>	<b>133</b>
6.1	Introduction	133
6.2	Forced-Vibration Nonlinear Mechanism	133
6.3	Self-Powered Tire-Pressure-Monitoring Systems	138
6.4	Self-Powered 5G NB-IoT System	140
6.5	Summary	143
	References	145
<b>7</b>	<b>Fluid-Induced Piezoelectric Energy Harvesters</b>	<b>153</b>
7.1	Introduction	153
7.2	Types of Flow-Induced PEH	153
7.2.1	Rotating-Type PEH	153
7.2.2	Flutter-Type PEH	156
7.2.3	Galloping-Type PEH	157
7.2.4	Vortex-Excited Vibration	158
7.3	Water Vortex-Shedding-Induced PEH	160
7.4	Aeroacoustics-Driven Jet-Stream Wind Energy Harvester	161
7.5	Summary	165
	References	166
<b>8</b>	<b>Wearable Flexible Piezoelectric Energy Harvesters</b>	<b>171</b>
8.1	Introduction	171
8.2	Fiber Structure PEH	172
8.3	Film Structure PEH	174
8.3.1	Hand Motion	174
8.3.2	Wrist and Elbow Motion	175
8.3.3	Knee-Joint Energy Harvesting	176
8.3.4	Foot Motion	177
8.3.5	Clothes Motion	178
8.3.6	Backpack	180

8.3.7	Joint Rotation	180
8.4	Summary	181
	References	182
<b>9</b>	<b>Implantable Piezoelectric Energy Harvesters</b>	<b>187</b>
9.1	Introduction	187
9.2	ZnO Nanowires-Based IPEH	188
9.3	PVDF-Based IPEH	189
9.4	Ceramic-Type IPEH	189
9.5	Summary	192
	References	193
<b>10</b>	<b>Flexible Piezoelectric Sensors</b>	<b>199</b>
10.1	Introduction	199
10.2	Working Principle	199
10.3	Flexible Piezoelectric Sensors	200
10.3.1	Pressure/Force Sensor	200
10.3.2	Strain Sensor	202
10.3.3	Ultrasonic Sensor	203
10.3.4	Wearable Piezoelectric Other Sensors	206
10.4	Piezoelectric Static Sensing	207
10.5	Wireless Communication	207
10.6	Application in Body Sensor Network	209
	References	211
<b>11</b>	<b>Artificial Intelligence Algorithm for Flexible Sensors</b>	<b>217</b>
11.1	Introduction	217
11.2	Artificial Intelligence Algorithm	219
11.2.1	ML Algorithms and DL Algorithms	219
11.2.2	Application of ML Algorithms	222
11.2.3	Intelligent Glove Platforms	225
11.3	Applications for IoTs System	231
11.3.1	Application of Piezoelectric Sensor	231
11.3.2	Hybrid Self-Powered Flexible Sensor	236
11.3.3	Application of Triboelectric Sensor	238
11.3.4	Future Directions	248
	References	248
	<b>Index</b>	<b>267</b>