

Contents

	<i>Preface</i>	<i>page xi</i>
1	Introduction	1
1.1	Wireless Sensing Platforms	1
1.2	Energy Harvesting Revolution	2
1.3	This Book	2
2	2D-3D 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 Nanotubes – CNTs)	15
2.4	Nanowire-Based Piezoelectric Nanogenerators	16
2.5	Nanotechnology-Based Capacitors	17
2.6	Problems and Questions	19
3	Solar (Light) Energy Harvesting	21
3.1	Introduction	21
3.2	History	21
3.3	Light Sources and Measures	23
3.4	Efficiency of Solar Cells	24
3.5	Ultimate Solar Cell Efficiency	25
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

	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 Solar Antennas and Rectennas	38
	3.11 Problems and Questions	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	Thermal Energy Harvesting	58
	5.1 Introduction	58
	5.2 Thermoelectric Phenomena	58
	5.2.1 The Seebeck Effect	58
	5.2.2 The Peltier Effect	59
	5.2.3 The Thomson Effect	60
	5.2.4 The Kelvin Relationships	60
	5.3 Thermoelectric Generators	60
	5.4 Heat Transfer Fundamentals	61
	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	75
	6.1 Introduction	75
	6.2 Historical Perspective	77
	6.3 Near-Field Wireless Power Transmission	79

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
6.3.7	Multiresonator Systems	93
6.4	Capacitive Power Transfer	97
6.5	Far-Field Wireless Power Transmission	99
6.6	RF-to-dc Conversion: the Rectifier	100
6.6.1	Time Reversal Duality	104
6.7	Far-Field Wireless Power Transmission at Millimeter Wave Frequencies and Beyond	107
6.8	Problems and Questions	108
7	Electromagnetic 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	Power 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
8.3.2	The Boost Converter	148
8.4	Summary of Switched Mode Power Converter Properties	155
8.5	Batteries and Supercapacitors	158
8.6	Problems and Questions	162
9	A System Perspective	163
9.1	Introduction	163
9.2	Wireless Sensing Platforms	163
9.3	Voltage Conversion Circuits for Energy Harvesting Transducers	165
9.4	Low-Power Microcontroller Units (MCU)	167
9.5	Sensor Circuits	168
9.6	Wireless Transceivers and Backscatter Communication	169

9.7	Energy Consumption	172
9.8	Ambient Backscattering	173
9.9	Problems and Questions	173
	<i>References</i>	175
	<i>Index</i>	194