

Contents

	Foreword	<i>ix</i>
	Preface	<i>xi</i>
	List of Abbreviations	<i>xv</i>
1	Introduction	<i>1</i>
	References	<i>3</i>
2	Some Basics	<i>5</i>
2.1	Measurement	<i>5</i>
2.1.1	Limitations of Measurement Uncertainty	<i>5</i>
2.1.1.1	The Fundamental Quantum Limit	<i>6</i>
2.1.1.2	Noise	<i>7</i>
2.2	The SI (Système International d'Unités)	<i>9</i>
2.2.1	The Second: Unit of Time	<i>11</i>
2.2.2	The Meter: Unit of Length	<i>13</i>
2.2.3	The Kilogram: Unit of Mass	<i>14</i>
2.2.4	The Ampere: Unit of Electric Current	<i>15</i>
2.2.5	The Kelvin: Unit of Thermodynamic Temperature	<i>16</i>
2.2.6	The Mole: Unit of Amount of Substance	<i>18</i>
2.2.7	The Candela: Unit of Luminous Intensity	<i>19</i>
2.2.8	Summary: Base and Derived Units of the SI	<i>21</i>
	References	<i>21</i>
3	Realization of the SI Second: Thermal Beam Cs Clock, Laser Cooling, and the Cs Fountain Clock	<i>23</i>
3.1	The Thermal Beam Cs Clock	<i>25</i>
3.2	Techniques for Laser Cooling and Trapping of Atoms	<i>28</i>
3.2.1	Doppler Cooling, Optical Molasses, and Magneto-Optical Traps	<i>29</i>
3.2.2	Cooling Below the Doppler Limit	<i>31</i>
3.3	The Cs Fountain Clock	<i>32</i>
	References	<i>35</i>
4	Flux Quanta, Josephson Effect, and the SI Volt	<i>39</i>
4.1	Josephson Effect and Quantum Voltage Standards	<i>39</i>

4.1.1	Basics of Superconductivity	39
4.1.2	Basics of the Josephson Effect	41
4.1.2.1	AC and DC Josephson Effect	42
4.1.2.2	Mixed DC and AC Voltages: Shapiro Steps	43
4.1.3	Basic Physics of Real Josephson Junctions	44
4.1.4	Josephson Voltage Standards	46
4.1.4.1	General Overview: Materials and Technology of Josephson Arrays	47
4.1.4.2	SIS Josephson Voltage Standards	48
4.1.4.3	Programmable Binary Josephson Voltage Standards	50
4.1.4.4	Pulse-Driven AC Josephson Voltage Standards	53
4.1.5	Metrology with Josephson Voltage Standards	57
4.1.5.1	DC Voltage, the SI Volt	57
4.1.5.2	The Conventional Volt in the Previous SI	59
4.1.5.3	AC Measurements with Josephson Voltage Standards	59
4.2	Flux Quanta and SQUIDs	62
4.2.1	Superconductors in External Magnetic Fields	62
4.2.1.1	Meissner–Ochsenfeld Effect	63
4.2.1.2	Flux Quantization in Superconducting Rings	65
4.2.1.3	Josephson Junctions in External Magnetic Fields and Quantum Interference	66
4.2.2	Basics of SQUIDs	67
4.2.3	Applications of SQUIDs in Measurement	71
4.2.3.1	Real DC SQUIDs	71
4.2.3.2	SQUID Magnetometers and Magnetic Property Measurement Systems	73
4.2.3.3	Cryogenic Current Comparators: Current and Resistance Ratios	74
4.2.3.4	Biomagnetic Measurements	76
4.3	Traceable Magnetic Flux Density Measurements	77
	References	80
5	Quantum Hall Effect, the SI Ohm, and the SI Farad	87
5.1	Basic Physics of Three- and Two-Dimensional Semiconductors	88
5.1.1	Three-Dimensional Semiconductors	88
5.1.2	Two-Dimensional Semiconductors	90
5.2	Two-Dimensional Electron Systems in Real Semiconductors	91
5.2.1	Basic Properties of Semiconductor Heterostructures	92
5.2.2	Epitaxial Growth of Semiconductor Heterostructures	93
5.2.3	Semiconductor Quantum Wells	94
5.2.4	Modulation Doping	95
5.3	The Hall Effect	97
5.3.1	The Classical Hall Effect	97
5.3.1.1	The Classical Hall Effect in Three Dimensions	97
5.3.1.2	The Classical Hall Effect in Two Dimensions	98
5.3.2	Physics of the Quantum Hall Effect	99
5.4	Metrology Using the Quantum Hall Effect	103
5.4.1	DC Quantum Hall Resistance Standards, the SI Ohm	103
5.4.2	The Conventional Ohm in the Previous SI	104

5.4.3	Technology of DC Quantum Hall Resistance Standards and Resistance Scaling	106
5.4.4	AC Quantum Hall Resistance Standards, the SI Farad	108
5.4.5	Relation Between Electrical Metrology and the Fine-Structure Constant	110
5.5	Graphene for Resistance Metrology	111
5.5.1	Basic Properties of Graphene	111
5.5.2	Fabrication of Graphene Monolayers for Resistance Metrology	113
5.5.3	Quantum Hall Effect in Monolayer Graphene	115
	References	117
6	Single-Charge Transfer Devices and the SI Ampere	123
6.1	Basic Physics of Single-Electron Transport	124
6.1.1	Single-Electron Tunneling	124
6.1.2	Coulomb Blockade in SET Transistors	125
6.1.3	Coulomb Blockade Oscillations and Single-Electron Detection	127
6.1.4	Clocked Single-Electron Transfer	129
6.2	Quantized Current Sources	130
6.2.1	Metallic Single-Electron Pumps	131
6.2.2	Semiconducting Quantized Current Sources	133
6.2.2.1	GaAs-Based SET Devices	133
6.2.2.2	Silicon-Based SET Devices	137
6.2.3	Superconducting Quantized Current Sources	138
6.2.4	Self-Referenced Quantized Current Sources	140
6.3	Realization of the SI Ampere	142
6.3.1	Ampere Realization via the SI Volt and SI Ohm	142
6.3.2	Direct Ampere Realization with Quantized Current Sources	144
6.4	Consistency Tests: Quantum Metrology Triangle	144
	References	146
7	The SI Kilogram, the Mole, and the Planck Constant	153
7.1	From “Monitoring the Stability of the Kilogram” to the Planck Constant	156
7.2	The Avogadro Experiment	158
7.3	The Kibble Balance Experiment	165
7.4	The Mole: Unit of Amount of Substance	169
7.5	The CODATA Evaluation of the Value of the Defining Planck Constant and the Maintenance and Dissemination of the Kilogram	170
7.5.1	The CODATA Evaluation and the Final Value of the Defining Planck Constant, h	170
7.5.2	Realization, Maintenance, and Dissemination of the Kilogram	172
	References	173
8	The SI Kelvin and the Boltzmann Constant	181
8.1	Primary Thermometers	182
8.1.1	Dielectric Constant Gas Thermometry	183
8.1.2	Acoustic Gas Thermometry	184

- 8.1.3 Radiation Thermometry 186
- 8.1.4 Doppler Broadening Thermometry 187
- 8.1.5 Johnson Noise Thermometry 189
- 8.1.6 Coulomb Blockade Thermometry 191
- 8.2 The CODATA Evaluation of the Value of the Defining Boltzmann Constant, Realization and Dissemination of the New Kelvin 193
- 8.2.1 The CODATA Evaluation of the Final Value of the Defining Boltzmann Constant 193
- 8.2.2 Realization and Dissemination of the Kelvin 194
- References 194

9 Beyond the Present SI: Optical Clocks and Quantum Radiometry 201

- 9.1 Optical Clocks and a New Second 201
- 9.1.1 Femtosecond Frequency Combs 204
- 9.1.2 Trapping of Ions and Neutral Atoms for Optical Clocks 209
- 9.1.2.1 Ion Traps 209
- 9.1.2.2 Optical Lattices 211
- 9.1.3 Neutral Atomic clocks 211
- 9.1.4 Atomic Ion Clocks 214
- 9.1.5 Possible Variation of the Fine-Structure Constant, α 217
- 9.2 Single-Photon Metrology and Quantum Radiometry 220
- 9.2.1 Single-Photon Sources 222
- 9.2.1.1 (NV) Color Centers in Diamond 223
- 9.2.1.2 Semiconductor Quantum Dots 225
- 9.2.2 Single-Photon Detectors 227
- 9.2.2.1 Nonphoton-Number-Resolving Detectors 227
- 9.2.2.2 Photon-Number-Resolving Detectors 228
- 9.2.3 Metrological Challenge 229
- References 230

10 Outlook 245

References 246

Index 247