

Contents

Foreword *IX*

Preface *XI*

List of Abbreviations *XIII*

Color Plates *XVII*

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>10</i>
2.2.1	The Second: Unit of Time	<i>11</i>
2.2.2	The Meter: Unit of Length	<i>14</i>
2.2.3	The Kilogram: Unit of Mass	<i>15</i>
2.2.4	The Ampere: Unit of Electrical Current	<i>17</i>
2.2.5	The Kelvin: Unit of Thermodynamic Temperature	<i>18</i>
2.2.6	The Mole: Unit of Amount of Substance	<i>19</i>
2.2.7	The Candela: Unit of Luminous Intensity	<i>20</i>
	References	<i>21</i>
3	Laser Cooling, Atomic Clocks, and the Second	<i>23</i>
3.1	Techniques for Laser Cooling	<i>25</i>
3.1.1	Doppler Cooling, Optical Molasses, and Magneto-Optical Traps	<i>26</i>
3.1.2	Cooling Below the Doppler Limit	<i>28</i>
3.1.3	Optical Lattices	<i>29</i>
3.1.4	Ion Traps	<i>30</i>
3.2	The Cs Fountain Clock	<i>32</i>
3.3	Optical Clocks	<i>36</i>
3.3.1	Femtosecond Frequency Combs	<i>38</i>
3.3.2	Neutral Atom Clocks	<i>43</i>

3.3.3	Atomic Ion Clocks	46
3.3.4	Possible Variation of the Fine-Structure Constant, α	49
	References	51
4	Superconductivity, Josephson Effect, and Flux Quanta	61
4.1	Josephson Effect and Quantum Voltage Standards	61
4.1.1	Brief Introduction to Superconductivity	61
4.1.2	Basics of the Josephson Effect	63
4.1.2.1	AC and DC Josephson Effect	64
4.1.2.2	Mixed DC and AC Voltages: Shapiro Steps	65
4.1.3	Basic Physics of Real Josephson Junctions	66
4.1.4	Josephson Voltage Standards	68
4.1.4.1	General Overview: Materials and Technology of Josephson Arrays	69
4.1.4.2	DC Josephson Voltage Standards: The Conventional Volt	70
4.1.4.3	Programmable Binary AC Josephson Voltage Standards	73
4.1.4.4	Pulse-Driven AC Josephson Voltage Standards	76
4.1.4.5	Applications of AC Josephson Voltage Standards	79
4.2	Flux Quanta and SQUIDs	81
4.2.1	Superconductors in External Magnetic Fields	82
4.2.1.1	Meissner–Ochsenfeld Effect	82
4.2.1.2	Flux Quantization in Superconducting Rings	84
4.2.1.3	Josephson Junctions in External Magnetic Fields and Quantum Interference	85
4.2.2	Basics of SQUIDs	87
4.2.3	Applications of SQUIDs in Measurement	90
4.2.3.1	Real DC SQUIDs	91
4.2.3.2	SQUID Magnetometers and Magnetic Property Measurement Systems	92
4.2.3.3	Cryogenic Current Comparators: Current and Resistance Ratios	94
4.2.3.4	Biomagnetic Measurements	96
4.2.4	Traceable Magnetic Flux Density Measurements	97
	References	99
5	Quantum Hall Effect	103
5.1	Basic Physics of Three- and Two-Dimensional Semiconductors	103
5.1.1	Three-Dimensional Semiconductors	104
5.1.2	Two-Dimensional Semiconductors	106
5.2	Two-Dimensional Electron Systems in Real Semiconductors	108
5.2.1	Basic Properties of Semiconductor Heterostructures	108
5.2.2	Epitaxial Growth of Semiconductor Heterostructures	110
5.2.3	Semiconductor Quantum Wells	111
5.2.4	Modulation Doping	112
5.3	The Hall Effect	114
5.3.1	The Classical Hall Effect	114

5.3.1.1	The Classical Hall Effect in Three Dimensions	114
5.3.1.2	The Classical Hall Effect in Two Dimensions	115
5.3.2	Physics of the Quantum Hall Effect	116
5.4	Quantum Hall Resistance Standards	119
5.4.1	DC Quantum Hall Resistance Standards	120
5.4.1.1	Comparison Between Classical and Quantum-Based Resistance Metrology	120
5.4.1.2	The Conventional Ohm	121
5.4.1.3	Technology of DC Quantum Hall Resistance Standards and Resistance Scaling	122
5.4.1.4	Relation Between the von Klitzing Constant and the Fine-Structure Constant	124
5.4.2	AC Quantum Hall Resistance Standards	125
	References	127
6	Single-Charge Transfer Devices and the New Ampere	131
6.1	Basic Physics of Single-Electron Transport	132
6.1.1	Single-Electron Tunneling	132
6.1.2	Coulomb Blockade in SET Transistors	133
6.1.3	Coulomb Blockade Oscillations and Single-Electron Detection	135
6.1.4	Clocked Single-Electron Transfer	137
6.2	Quantized Current Sources	139
6.2.1	Metallic Single-Electron Pumps	139
6.2.2	Semiconducting Quantized Current Sources	141
6.2.2.1	GaAs Based SET Devices	142
6.2.2.2	Silicon-Based SET Devices	145
6.2.3	Superconducting Quantized Current Sources	145
6.2.4	A Quantum Standard of Current Based on Single-Electron Transfer	148
6.3	Consistency Tests: Quantum Metrology Triangle	149
	References	151
7	The Planck Constant, the New Kilogram, and the Mole	155
7.1	The Avogadro Experiment	158
7.2	The Watt Balance Experiment	165
7.3	The Mole: Unit of Amount of Substance	169
	References	170
8	Boltzmann Constant and the New Kelvin	175
8.1	Primary Thermometers	176
8.1.1	Dielectric Constant Gas Thermometry	177
8.1.2	Acoustic Gas Thermometry	178
8.1.3	Radiation Thermometry	180
8.1.4	Doppler Broadening Thermometry	181
8.1.5	Johnson Noise Thermometry	183

8.1.6	Coulomb Blockade Thermometry	185
8.2	Realization and Dissemination of the New Kelvin	186
	References	186
9	Single-Photon Metrology and Quantum Radiometry	191
9.1	Single-Photon Sources	193
9.1.1	(NV) Color Centers in Diamond	194
9.1.2	Semiconductor Quantum Dots	196
9.2	Single-Photon Detectors	198
9.2.1	Nonphoton-Number Resolving Detectors	199
9.2.2	Photon-Number-Resolving Detectors	199
9.3	Metrological Challenge	201
	References	202
10	Outlook	207
	References	208
	Index	209