

Contents

1	Electrons	1
1.1	Introduction	1
1.2	de Broglie's Second Idea	3
1.3	The Pauli Exclusion Principle	8
1.4	Fermi-Dirac Statistics	9
1.5	The Schrödinger Equation	11
1.6	de Broglie's First Idea	12
1.7	Summary	15
	Exercises	15
	References	16
2	Photons	19
2.1	Introduction	19
2.1.1	Photon Properties	20
2.1.2	Brief History of Photons	21
2.2	Bose Einstein Statistics	24
2.3	Propagation of Photons	26
2.3.1	Maxwell's Equations	26
2.3.2	Reflection and Transmission: Fresnel's Equations	30
2.3.3	Single Photon Behavior	33
2.4	Wave Behavior of Photons	34
2.4.1	Computational Examples	34
2.4.2	Young's Double Slit Experiment	38
2.4.3	Single Photons	41
2.4.4	The Copenhagen Interpretation of Quantum Measurements	46
2.5	Quantum Entanglement	47
2.6	Summary	48
	Exercises	49
	References	55

3 Free Electron Behavior in Semiconductor Heterostructures	57
3.1 Introduction	57
3.2 The Schrödinger Equation	58
3.3 Quantized Energy Levels for Electrons in an Infinitely Deep Potential Well	58
3.3.1 Potential Well with Infinitely High Boundaries	58
3.3.2 Boundary Conditions	59
3.4 Electrons Confined by a Square Potential Well with Finite Barriers	61
3.4.1 Boundary Conditions	63
3.4.2 Discussion of Results for Quantization of Energy Levels in a Square Potential Well	65
3.4.3 Energy Levels in a Quantum Well in the Presence of an Electric Field: The Quantum-Confining Stark Effect	66
3.5 Quantum-Mechanical Tunneling	67
3.6 Tunneling in p-n Junction Diodes	75
3.7 Tunneling in the Presence of Multiple Barriers	81
3.8 Tunneling Time	86
3.8.1 Wavepackets	87
3.8.2 Detection of a Wavepacket Representing a Single Particle	88
3.8.3 Relative Time of Flight	93
3.8.4 Analysis of the Wavepacket: Phase-Delay Tunneling Time	96
3.8.5 Tunneling Time: Some Conclusions	101
3.9 Summary	102
Exercises	103
Appendix: Source Code for Calculation of Sequential Tunneling Using MATLAB	106
References	108
4 Electronic Energy Levels in Crystalline Semiconductors	111
4.1 Introduction	111
4.2 Periodicity	112
4.3 Periodicity and Electron Energy States	114
4.4 Brillouin Zones	117
4.5 Electronic Bandstructure of Specific Materials: Integrating the Crystal Potential	123
4.5.1 Introduction	123
4.5.2 Schrödinger's Equation in a Periodic Potential	124
4.6 Energy Bandstructure of Silicon	127
4.7 Energy Bandstructure of Germanium	130
4.8 Energy Bandstructure of Gallium Arsenide	133
4.9 Materials with Multiple Electrons	137

4.9.1	The Hohenberg-Kohn Theorem and Density Functional Theory	139
4.9.2	The Kohn-Sham Equations	142
4.9.3	Using Density Functional Theory to Analyze Real Systems	143
4.10	Summary	144
	Exercises	145
	Appendix: Source Code for Bandstructure Calculation Using MATLAB	147
	References	150
5	The Harmonic Oscillator and Quantization of Electromagnetic Fields	151
5.1	Introduction	151
5.2	The Harmonic Oscillator	152
5.3	Raising and Lowering Operators	154
5.4	Quantization of the Electromagnetic Fields	156
5.5	Spontaneous Parametric Down-Conversion	159
5.6	Two-Photon Interference	165
5.7	Summary	172
	Exercises	173
	References	174
6	Entanglement and Non-locality of Quantum Photonics	177
6.1	Introduction	177
6.2	The Einstein, Podolsky Rosen Paradox: Is the Description of Reality by Quantum Mechanics Complete?	179
6.2.1	Entangled States in Quantum Mechanics	179
6.2.2	Measurements of Photon Polarization	182
6.2.3	Joint Polarization Measurements	183
6.3	Bell's Theorem	186
6.3.1	John S. Bell and the Completeness of Quantum Mechanics	186
6.3.2	Hidden Variables in Quantum Mechanics	187
6.3.3	Experiments	191
6.4	More About Bell's Theorem—Loopholes, Bohm—deBroglie and Free-Will	194
6.4.1	Bell Test Experiments—Loopholes	195
6.4.2	Locality, Reality and Free-Choice	197
6.4.3	Free-Will	197
6.5	Summary	198
	Exercises	199
	References	200

7 Lasers.....	201
7.1 Introduction	201
7.2 Spontaneous and Stimulated Emission	202
7.3 Laser Action.....	206
7.3.1 Analysis of Spontaneous and Stimulated Emission—A Macroscopic Description	206
7.3.2 Optical Gain	209
7.3.3 $N_2 > N_1$: Population Inversion	212
7.4 Semiconductor Diode Lasers	215
7.4.1 Population Inversion in Semiconductor Materials	216
7.4.2 Optical Feedback—Making a Laser.	218
7.4.3 Laser Threshold.	221
7.5 Laser Engineering.....	223
7.5.1 Heterostructure Lasers.....	223
7.5.2 Optical Confinement—Waveguiding	224
7.5.3 Buried Heterostructure Lasers	226
7.5.4 Separate Confinement of Photons and Electrons	228
7.5.5 The Quantum Well Laser	232
7.6 Summary	233
Exercises.....	235
References.....	235
8 Quantum Cascade Lasers.....	237
8.1 Introduction	237
8.2 Requirements for an Intersubband Laser.....	240
8.3 Injector Region.....	241
8.4 Electron Evacuation from the Lower Level	243
8.5 Photon Emission Region.....	250
8.5.1 Introduction.....	250
8.5.2 Intersubband Optical Transitions	250
8.5.3 Spontaneous and Stimulated Emission.	255
8.6 Current-Voltage and Light-Current Relationship.....	255
8.6.1 Rate Equations	256
8.7 Interband Cascade Lasers	258
8.7.1 ICL Active Region Design	259
8.7.2 Hole Injection by Tunneling	260
8.8 Summary	261
Exercises.....	262
References.....	264
9 Non-linear Optics: Second-Harmonic Generation and Parametric Oscillation.....	267
9.1 Introduction	267
9.2 Non-linear Response of Optical Materials.....	268

9.3	Electromagnetic Wave Propagation in Non-linear Materials	273
9.3.1	Application to Second Harmonic Generation	277
9.3.2	Application to Parametric Amplification	280
9.4	Summary	283
	Exercises	285
	References	285
Index	287