

Contents

1	Introduction	1
1.1	Classification of optical processes	1
1.2	Optical coefficients	2
1.3	The complex refractive index and dielectric constant	6
1.4	Optical materials	9
1.4.1	Crystalline insulators and semiconductors	9
1.4.2	Glasses	12
1.4.3	Metals	13
1.4.4	Molecular materials	14
1.4.5	Doped glasses and insulators	16
1.5	Characteristic optical physics in the solid state	17
1.5.1	Crystal symmetry	18
1.5.2	Electronic bands	20
1.5.3	Vibronic bands	21
1.5.4	The density of states	21
1.5.5	Delocalized states and collective excitations	22
1.6	Microscopic models	23
	Chapter summary	24
	Further reading	25
	Exercises	25
2	Classical propagation	28
2.1	Propagation of light in a dense optical medium	28
2.1.1	Atomic oscillators	29
2.1.2	Vibrational oscillators	31
2.1.3	Free electron oscillators	32
2.2	The dipole oscillator model	33
2.2.1	The Lorentz oscillator	33
2.2.2	Multiple resonances	38
2.2.3	Comparison with experimental data	41
2.2.4	Local field corrections	43
2.3	The Kramers–Kronig relationships	44
2.4	Dispersion	46
2.5	Optical anisotropy	48
2.5.1	Natural anisotropy: birefringence	48
2.5.2	Induced optical anisotropy	53
2.6	Optical chirality	55
	Chapter summary	57
	Further reading	58

Exercises	58
3 Interband absorption	62
3.1 Interband transitions	62
3.2 The transition rate for direct absorption	64
3.3 Band edge absorption in direct gap semiconductors	68
3.3.1 The atomic physics of the interband transitions	68
3.3.2 The band structure of a direct gap III-V semiconductor	69
3.3.3 The joint density of states	71
3.3.4 The frequency dependence of the band edge absorption	72
3.3.5 The Franz-Keldysh effect	74
3.3.6 Band edge absorption in a magnetic field	75
3.3.7 Spin injection	77
3.4 Band edge absorption in indirect gap semiconductors	79
3.5 Interband absorption above the band edge	82
3.6 Measurement of absorption spectra	84
3.7 Semiconductor photodetectors	86
3.7.1 Photodiodes	87
3.7.2 Photoconductive devices	89
3.7.3 Photovoltaic devices	90
Chapter summary	91
Further reading	92
Exercises	92
4 Excitons	95
4.1 The concept of excitons	95
4.2 Free excitons	96
4.2.1 Binding energy and radius	96
4.2.2 Exciton absorption	98
4.2.3 Experimental data for free excitons in GaAs	100
4.3 Free excitons in external fields	101
4.3.1 Electric fields	102
4.3.2 Magnetic fields	103
4.4 Free excitons at high densities	104
4.5 Frenkel excitons	107
4.5.1 Rare gas crystals	107
4.5.2 Alkali halides	108
4.5.3 Molecular crystals	108
Chapter summary	109
Further reading	110
Exercises	110
5 Luminescence	113
5.1 Light emission in solids	113
5.2 Interband luminescence	115
5.2.1 Direct gap materials	116

5.2.2	Indirect gap materials	117
5.3	Photoluminescence	118
5.3.1	Excitation and relaxation	118
5.3.2	Low carrier densities	120
5.3.3	Degeneracy	121
5.3.4	Optical orientation	123
5.3.5	Photoluminescence spectroscopy	125
5.4	Electroluminescence	126
5.4.1	General principles of electroluminescent devices	126
5.4.2	Light-emitting diodes	129
5.4.3	Diode lasers	130
5.4.4	Cathodoluminescence	135
	Chapter summary	136
	Further reading	137
	Exercises	138
6	Quantum confinement	141
6.1	Quantum-confined structures	141
6.2	Growth and structure of quantum wells	144
6.3	Electronic levels	146
6.3.1	Separation of the variables	146
6.3.2	Infinite potential wells	147
6.3.3	Finite potential wells	149
6.4	Quantum well absorption and excitons	152
6.4.1	Selection rules	152
6.4.2	Two-dimensional absorption	154
6.4.3	Experimental data	156
6.4.4	Excitons in quantum wells	157
6.4.5	Spin injection in quantum wells	158
6.5	The quantum-confined Stark effect	160
6.6	Optical emission	164
6.7	Intersubband transitions	166
6.8	Quantum dots	167
6.8.1	Quantum dots as artificial atoms	167
6.8.2	Colloidal quantum dots	170
6.8.3	Self-assembled epitaxial quantum dots	172
	Chapter summary	174
	Further reading	175
	Exercises	176
7	Free electrons	180
7.1	Plasma reflectivity	180
7.2	Free carrier conductivity	183
7.3	Metals	185
7.3.1	The Drude model	185
7.3.2	Interband transitions in metals	188
7.4	Doped semiconductors	191
7.4.1	Free carrier reflectivity and absorption	191

7.4.2	Impurity absorption	196
7.5	Plasmons	198
7.5.1	Bulk plasmons	198
7.5.2	Surface plasmons	202
7.6	Negative refraction	207
	Chapter summary	209
	Further reading	210
	Exercises	211
8	Molecular materials	214
8.1	Introduction to organic materials	214
8.2	Optical spectra of molecules	216
8.2.1	Electronic states and transitions	216
8.2.2	Vibronic coupling	218
8.2.3	Molecular configuration diagrams	219
8.2.4	The Franck–Condon principle	221
8.2.5	Experimental spectra	224
8.3	Conjugated molecules	227
8.3.1	Small conjugated molecules	227
8.3.2	Conjugated polymers	229
8.4	Organic opto-electronics	232
8.5	Carbon nanostructures	235
8.5.1	Introduction	235
8.5.2	Graphene	236
8.5.3	Carbon nanotubes	237
8.5.4	Carbon bucky balls	241
	Chapter summary	243
	Further reading	244
	Exercises	245
9	Luminescence centres	247
9.1	Vibronic absorption and emission	247
9.2	Colour centres	250
9.2.1	F-centres in alkali halides	250
9.2.2	NV centres in diamond	253
9.3	Paramagnetic impurities in ionic crystals	255
9.3.1	The crystal-field effect and vibronic coupling	255
9.3.2	Rare-earth ions	257
9.3.3	Transition-metal ions	259
9.4	Solid-state lasers and optical amplifiers	261
9.5	Phosphors	264
	Chapter summary	266
	Further reading	267
	Exercises	268
10	Phonons	271
10.1	Infrared active phonons	271
10.2	Infrared reflectivity and absorption in polar solids	273

10.2.1	The classical oscillator model	273
10.2.2	The Lyddane–Sachs–Teller relationship	276
10.2.3	Reststrahlen	277
10.2.4	Lattice absorption	278
10.3	Polaritons	281
10.4	Polarons	282
10.5	Inelastic light scattering	285
10.5.1	General principles of inelastic light scattering	286
10.5.2	Raman scattering	287
10.5.3	Brillouin scattering	289
10.6	Phonon lifetimes	290
	Chapter summary	292
	Further reading	292
	Exercises	293
11	Nonlinear optics	295
11.1	The nonlinear susceptibility tensor	295
11.2	The physical origin of optical nonlinearities	298
11.2.1	Non-resonant nonlinearities	299
11.2.2	Resonant nonlinearities	302
11.3	Second-order nonlinearities	305
11.3.1	Nonlinear frequency mixing	305
11.3.2	Effect of crystal symmetry	308
11.3.3	Phase matching	310
11.3.4	Electro-optics	313
11.4	Third-order nonlinear effects	317
11.4.1	Overview of third-order phenomena	317
11.4.2	Frequency tripling	318
11.4.3	The optical Kerr effect and the nonlinear refractive index	318
11.4.4	Stimulated Raman scattering	321
11.4.5	Isotropic third-order nonlinear media	321
11.4.6	Nonlinear propagation in optical fibres and solitons	322
11.4.7	Resonant nonlinearities in semiconductors	324
	Chapter summary	326
	Further reading	327
	Exercises	328
A	Electromagnetism in dielectrics	330
A.1	Electromagnetic fields and Maxwell's equations	330
A.2	Electromagnetic waves	333
	Further reading	339
B	Quantum theory of radiative absorption and emission	340
B.1	Einstein coefficients	340
B.2	Quantum transition rates	344
B.3	Selection rules	347
	Further reading	349

C Angular momentum in atomic physics	350
C.1 Angular momentum in quantum mechanics	350
C.2 Notation for atomic angular momentum states	351
C.3 Sub-level splitting	352
Further reading	353
D Band theory	354
D.1 Metals, semiconductors, and insulators	354
D.2 The nearly free electron model	356
D.3 Example band structures	359
Further reading	362
E Semiconductor p-i-n diodes	363
Further reading	365
Solutions to exercises	366
Bibliography	376
Symbols	387
Index	389