Books in this series are written at the final year undergraduate and beginning graduate level, and provide straightforward introductions to key topics in physics today. Background material and applications as well as pointers to more advanced work are included, along with ample tutorial material, examples, illustrations, chapter summaries, and graded problem sets (with some answers and hints).

The second edition of this successful textbook provides an up-to-date account of the optical physics of solid-state materials. The basic principles of absorption, reflection, luminescence, and light scattering are covered for a wide range of materials, including insulators, semiconductors, and metals. The text starts with a review of classical optics, and then moves on to the treatment of optical transition rates by quantum theory. In addition to the traditional discussion of crystalline materials, glasses and molecular solids are also covered.

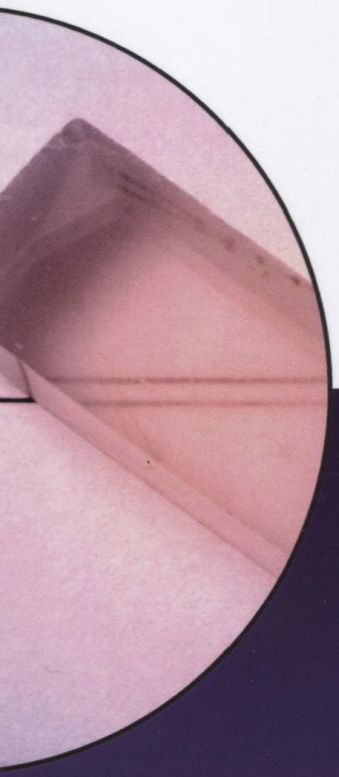
The first edition included a number of subjects that are not normally covered in standard texts, notably semiconductor quantum wells, molecular materials, vibronic solid-state lasers, and nonlinear optics. The basic structure of the second edition is unchanged, but all of the chapters have been updated and improved. Futhermore, a number of important new topics have been added, including: optical control of spin • quantum dots • plasmonics • negative refraction • carbon nanostructures (graphene, nanotubes and fullerenes) • NV centres in diamond.

The text is aimed at final year undergraduates, masters students, and researchers. It is mainly written for physicists, but might also be useful for electrical engineers, materials scientists, and physical chemists. The topics are written in a clear tutorial style with worked examples, chapter summaries, and exercises. A solutions manual is available on request for instructors.

Mark Fox is Professor of Optical Physics at the University of Sheffield.

'Fox has succeeded in offering a good, compact, senior level presentation of the optical properties of solids.'

American Journal of Physics



Cover image: Double refraction in a birefringent crystal. Photograph by S. Collins.

IN THE SAME SERIES

CONDENSED MATTER PHYSICS

Structure and dynamics: an atomic view of materials
M.T. Dove

Band theory and electronic properties of solids
J. Singleton

Magnetism in condensed matter
S.J. Blundell

Superconductivity, superfluids, and condensates
J.F. Annett

Soft condensed matter
R.A.L. Jones

ATOMIC, OPTICAL, AND LASER PHYSICS

Atomic physics
C.J. Foot

Modern classical optics
G.A. Brooker

Laser physics
S.M. Hooker, C.E. Webb

Quantum optics: an introduction
A.M. Fox

Quantum information
S.M. Barnett

OXFORD
UNIVERSITY PRESS

ISBN 978-0-19-957337-0

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