

Contents

Data on specific materials in text	xiii
Introduction	xv

1 The electron as a particle

1.1 Introduction	1
1.2 The effect of an electric field—conductivity and Ohm's law	2
1.3 The hydrodynamic model of electron flow	4
1.4 The Hall effect	5
1.5 Electromagnetic waves in solids	6
1.6 Waves in the presence of an applied magnetic field: cyclotron resonance	13
1.7 Plasma waves	16
1.8 Heat	19
Exercises	21

2 The electron as a wave

2.1 Introduction	23
2.2 The electron microscope	26
2.3 Some properties of waves	27
2.4 Applications to electrons	29
2.5 Two analogies	31
Exercises	33

3 The electron

3.1 Introduction	34
3.2 Schrödinger's equation	36
3.3 Solutions of Schrödinger's equation	37
3.4 The electron as a wave	38
3.5 The electron as a particle	39
3.6 The electron meeting a potential barrier	39
3.7 Two analogies	42
3.8 The electron in a potential well	43
3.9 The potential well with a rigid wall	45
3.10 The uncertainty relationship	45
3.11 Philosophical implications	46
Exercises	48

4 The hydrogen atom and the periodic table

4.1	The hydrogen atom	51
4.2	Quantum numbers	56
4.3	Electron spin and Pauli's exclusion principle	57
4.4	The periodic table	57
	Exercises	61

5 Bonds

5.1	Introduction	64
5.2	General mechanical properties of bonds	65
5.3	Bond types	67
5.3.1	Ionic bonds	67
5.3.2	Metallic bonds	68
5.3.3	The covalent bond	68
5.3.4	The van der Waals bond	71
5.3.5	Mixed bonds	72
5.3.6	Carbon again	72
5.4	Feynman's coupled mode approach	73
5.5	Nuclear forces	78
5.6	The hydrogen molecule	78
5.7	An analogy	79
	Exercises	80

6 The free electron theory of metals

6.1	Free electrons	81
6.2	The density of states and the Fermi–Dirac distribution	82
6.3	The specific heat of electrons	85
6.4	The work function	86
6.5	Thermionic emission	86
6.6	The Schottky effect	89
6.7	Field emission	92
6.8	The field-emission microscope	92
6.9	The photoelectric effect	93
6.10	Quartz–halogen lamps	95
6.11	The junction between two metals	95
	Exercises	96

7 The band theory of solids

7.1	Introduction	98
7.2	The Kronig–Penney model	99
7.3	The Ziman model	102
7.4	The Feynman model	106
7.5	The effective mass	109
7.6	The effective number of free electrons	111

7.7	The number of possible states per band	112
7.8	Metals and insulators	114
7.9	Holes	114
7.10	Divalent metals	116
7.11	Finite temperatures	117
7.12	Concluding remarks	118
	Exercises	119

8 Semiconductors

8.1	Introduction	120
8.2	Intrinsic semiconductors	120
8.3	Extrinsic semiconductors	125
8.4	Scattering	129
8.5	A relationship between electron and hole densities	131
8.6	III–V and II–VI compounds	133
8.7	Non-equilibrium processes	137
8.8	Real semiconductors	138
8.9	Amorphous semiconductors	140
8.10	Measurement of semiconductor properties	140
8.10.1	Mobility	140
8.10.2	Hall coefficient	143
8.10.3	Effective mass	143
8.10.4	Energy gap	144
8.10.5	Carrier lifetime	148
8.11	Preparation of pure and controlled-impurity single-crystal semiconductors	148
8.11.1	Crystal growth from the melt	148
8.11.2	Zone refining	149
8.11.3	Floating zone purification	150
8.11.4	Epitaxial growth	151
8.11.5	Molecular beam epitaxy	152
8.11.6	Metal–organic chemical vapour deposition	153
8.11.7	Hydride vapour phase epitaxy (HVPE) for nitride devices	154
	Exercises	155

9 Principles of semiconductor devices

9.1	Introduction	157
9.2	The p–n junction in equilibrium	157
9.3	Rectification	162
9.4	Injection	164
9.5	Junction capacity	166
9.6	The transistor	166
9.7	Metal–semiconductor junctions	172
9.8	The role of surface states; real metal–semiconductor junctions	174
9.9	Metal–insulator–semiconductor junctions	176
9.10	The tunnel diode	179
9.11	The backward diode	182
9.12	The Zener diode and the avalanche diode	182
9.12.1	Zener breakdown	183
9.12.2	Avalanche breakdown	183
9.13	Varactor diodes	184

9.14	Field-effect transistors	185
9.15	Heterostructures	190
9.16	Charge-coupled devices	194
9.17	Silicon controlled rectifier	196
9.18	The Gunn effect	197
9.19	Strain gauges	200
9.20	Measurement of magnetic field by the Hall effect	201
9.21	Gas sensors	201
9.22	Microelectronic circuits	201
9.23	Plasma etching	205
9.24	Recent techniques for overcoming limitations	207
9.25	Building in the third dimension	208
9.26	Microelectro-mechanical systems (MEMS)	209
9.26.1	A movable mirror	210
9.26.2	A mass spectrometer on a chip	211
9.27	Nanoelectronics	213
9.28	Social implications	217
	Exercises	218

10 Dielectric materials

10.1	Introduction	220
10.2	Macroscopic approach	220
10.3	Microscopic approach	221
10.4	Types of polarization	222
10.5	The complex dielectric constant and the refractive index	223
10.6	Frequency response	224
10.7	Anomalous dispersion	225
10.8	Polar and non-polar materials	226
10.9	The Debye equation	228
10.10	The effective field	229
10.11	Acoustic waves	231
10.12	Dielectric breakdown	235
10.12.1	Intrinsic breakdown	235
10.12.2	Thermal breakdown	235
10.12.3	Discharge breakdown	236
10.13	Piezoelectricity	236
10.14	Interaction of optical phonons with drifting electrons	241
10.15	Ferroelectrics	242
10.16	Optical fibres	243
10.17	The Xerox process	245
10.18	Liquid crystals	245
	Exercises	247

11 Magnetic materials

11.1	Introduction	249
11.2	Macroscopic approach	250
11.3	Microscopic theory (phenomenological)	250
11.4	Domains and the hysteresis curve	254

11.5	Soft magnetic materials	258
11.6	Hard magnetic materials (permanent magnets)	260
11.7	Microscopic theory (quantum-mechanical)	264
11.7.1	The Stern–Gerlach experiment	268
11.7.2	Paramagnetism	268
11.7.3	Paramagnetic solids	270
11.7.4	Antiferromagnetism	271
11.7.5	Ferromagnetism	271
11.7.6	Ferrimagnetism	272
11.7.7	Garnets	272
11.7.8	Helimagnetism	272
11.8	Magnetic resonance	272
11.8.1	Paramagnetic resonance	272
11.8.2	Electron spin resonance	273
11.8.3	Ferromagnetic, antiferromagnetic, and ferrimagnetic resonance	273
11.8.4	Nuclear magnetic resonance	273
11.8.5	Cyclotron resonance	274
11.8.6	The quantum Hall effect	274
11.9	Some applications	276
11.9.1	Magnetic bubbles	276
11.9.2	Magnetoresistance and spintronics	278
11.9.3	Isolators	282
11.9.4	Sensors	283
11.9.5	Medical imaging	283
11.9.6	Electric motors	284
	Exercises	284

12 Lasers

12.1	Equilibrium	286
12.2	Two-state systems	286
12.3	Lineshape function	290
12.4	Absorption and amplification	292
12.5	Resonators and conditions of oscillation	292
12.6	Some practical laser systems	293
12.6.1	Solid state lasers	294
12.6.2	The gaseous discharge laser	295
12.6.3	Dye lasers	296
12.6.4	Gas-dynamic lasers	297
12.6.5	Excimer lasers	298
12.6.6	Chemical lasers	298
12.7	Semiconductor lasers	298
12.7.1	Fundamentals	298
12.7.2	Wells, wires, and dots	303
12.7.3	Bandgap engineering	307
12.7.4	Quantum cascade lasers	309
12.8	Laser modes and control techniques	310
12.8.1	Transverse modes	310
12.8.2	Axial modes	311
12.8.3	Q switching	312
12.8.4	Cavity dumping	312
12.8.5	Mode locking	312
12.9	Parametric oscillators	313
12.10	Optical fibre amplifiers	314
12.11	Masers	315
12.12	Noise	317

x Contents

12.13	Applications	317
12.13.1	Nonlinear optics	318
12.13.2	Spectroscopy	318
12.13.3	Photochemistry	318
12.13.4	Study of rapid events	318
12.13.5	Plasma diagnostics	319
12.13.6	Plasma heating	319
12.13.7	Acoustics	319
12.13.8	Genetics	319
12.13.9	Metrology	319
12.13.10	Manipulation of atoms by light	319
12.13.11	Optical radar	320
12.13.12	Optical discs	320
12.13.13	Medical applications	321
12.13.14	Machining	321
12.13.15	Sensors	321
12.13.16	Communications	322
12.13.17	Nuclear applications	323
12.13.18	Holography	323
12.14	The atom laser	326
	Exercises	327

13 Optoelectronics

13.1	Introduction	328
13.2	Light detectors	329
13.3	Light emitting diodes (LEDs)	331
13.4	Electro-optic, photorefractive, and nonlinear materials	334
13.5	Volume holography and phase conjugation	336
13.6	Acousto-optic interaction	340
13.7	Integrated optics	342
13.7.1	Waveguides	344
13.7.2	Phase shifter	344
13.7.3	Directional coupler	345
13.7.4	Filters	347
13.8	Spatial light modulators	347
13.9	Nonlinear Fabry–Perot cavities	349
13.10	Optical switching	352
13.11	Electro-absorption in quantum well structures	354
13.11.1	Excitons	354
13.11.2	Excitons in quantum wells	355
13.11.3	Electro-absorption	355
13.11.4	Applications	357
	Exercises	359

14 Superconductivity

14.1	Introduction	361
14.2	The effect of a magnetic field	363
14.2.1	The critical magnetic field	363
14.2.2	The Meissner effect	364
14.3	Microscopic theory	365
14.4	Thermodynamical treatment	366
14.5	Surface energy	370
14.6	The Landau–Ginzburg theory	372

14.7	The energy gap	378
14.8	Some applications	382
14.8.1	High-field magnets	382
14.8.2	Switches and memory elements	383
14.8.3	Magnetometers	383
14.8.4	Metrology	384
14.8.5	Suspension systems and motors	384
14.8.6	Radiation detectors	385
14.8.7	Heat valves	385
14.9	High- T_c superconductors	385
14.10	New superconductors	390
	Exercises	392

15 Artificial materials or metamaterials

15.1	Introduction	394
15.2	Natural and artificial materials	395
15.3	Photonic bandgap materials	396
15.4	Equivalent plasma frequency of a wire medium	398
15.5	Resonant elements for metamaterials	400
15.6	Polarizability of a current-carrying resonant loop	401
15.7	Effective permeability	402
15.8	Effect of negative material constants	405
15.9	The 'perfect' lens	407
15.10	Detectors for magnetic resonance imaging	413
	Epilogue	415
	Appendix I: Organic semiconductors	417
	Appendix II: Nobel laureates	424
	Appendix III: Physical constants	426
	Appendix IV: Variational calculus. Derivation of Euler's equation	428
	Appendix V: Suggestions for further reading	430
	Answers to exercises	433
	Index	437