

# **Electrical Properties of Materials**

---

L. SOLYMAR and D. WALSH

*Department of Engineering Science  
University of Oxford*

SIXTH EDITION

OXFORD NEW YORK TOKYO  
OXFORD UNIVERSITY PRESS  
1998

# Contents

<b>Data on specific materials in text</b>	<b>xi</b>
<b>Introduction</b>	<b>xiii</b>
<b>1 The electron as a particle</b>	<b>1</b>
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	14
1.7 Cyclotron resonance	15
1.8 Plasma waves	18
1.9 Specific heat of metals	19
Exercises	20
<b>2 The electron as a wave</b>	<b>22</b>
2.1 Introduction	22
2.2 The electron microscope	25
2.3 Some properties of waves	26
2.4 Applications to electrons	28
2.5 Two analogies	31
Exercises	32
<b>3 The electron</b>	<b>34</b>
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	39
3.5 The electron as a particle	39
3.6 The electron meeting a potential barrier	40
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	46
3.11 Philosophical implications	47
Exercises	49
<b>4 The hydrogen atom and the periodic table</b>	<b>51</b>
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	58
Exercises	63

<b>5 Bonds</b>	<b>64</b>
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	69
5.3.4 The van der Waals bond	72
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
<b>Exercises</b>	80
<b>6 The free electron theory of metals</b>	<b>81</b>
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	87
6.6 The Schottky effect	93
6.7 Field emission	94
6.8 The field-emission microscope	96
6.9 The photoelectric effect	94
6.10 Quartz–halogen lamps	96
6.11 The junction between two metals	97
<b>Exercises</b>	98
<b>7 The band theory of solids</b>	<b>100</b>
7.1 Introduction	100
7.2 The Kronig–Penney model	101
7.3 The Ziman model	105
7.4 The Feynman model	108
7.5 The effective mass	111
7.6 The effective number of free electrons	113
7.7 The number of possible states per band	115
7.8 Metals and insulators	116
7.9 Holes	117
7.10 Divalent metals	118
7.11 Finite temperatures	119
7.12 Concluding remarks	121
<b>Exercises</b>	121
<b>8 Semiconductors</b>	<b>122</b>
8.1 Introduction	122
8.2 Intrinsic semiconductors	122
8.3 Extrinsic semiconductors	127

8.4 Scattering	132
8.5 A relationship between electron and hole densities	134
8.6 III-V and II-VI compounds	136
8.7 Non-equilibrium processes	138
8.8 Real semiconductors	139
8.9 Amorphous semiconductors	141
8.10 Measurement of semiconductor properties	141
8.10.1 Mobility	142
8.10.2 Hall coefficient	144
8.10.3 Effective mass	144
8.10.4 Energy gap	145
8.10.5 Carrier lifetime	148
8.11 Preparation of pure and controlled-impurity single-crystal semiconductors	149
8.11.1 Crystal growth from the melt	149
8.11.2 Zone refining	150
8.11.3 Floating zone purification	151
8.11.4 Epitaxial growth	151
8.11.5 Molecular beam epitaxy	153
8.11.6 Metal-organic chemical vapour deposition	154
<b>Exercises</b>	<b>154</b>

**9 Principles of semiconductor devices****157**

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	167
9.7 Metal-semiconductor junctions	173
9.8 The role of surface states; real metal-semiconductor junction	175
9.9 Metal-insulator-semiconductor junctions	177
9.10 The tunnel diode	180
9.11 The backward diode	183
9.12 The Zener diode and the avalanche diode	183
9.12.1 Zener breakdown	184
9.12.2 Avalanche breakdown	184
9.13 Varactor diodes	185
9.14 Field-effect transistors	187
9.15 Heterostructures	191
9.16 Charge-coupled devices	195
9.17 Silicon controlled rectifier	198
9.18 The Gunn effect	199
9.19 Strain gauges	201
9.20 Measurement of magnetic field by the Hall effect	202
9.21 Gas sensors	203
9.22 Microelectronic circuits	203
9.23 Nanoelectronics	208
9.24 Social implications	210
<b>Exercises</b>	<b>211</b>

<b>10 Dielectric materials</b>	<b>213</b>
10.1 Introduction	213
10.2 Macroscopic approach	213
10.3 Microscopic approach	214
10.4 Types of polarization	215
10.5 The complex dielectric constant and the refractive index	216
10.6 Frequency response	218
10.7 Polar and non-polar materials	219
10.8 The Debye equation	221
10.9 The effective field	222
10.10 Dielectric breakdown	223
10.10.1 Intrinsic breakdown	224
10.10.2 Thermal breakdown	224
10.10.3 Discharge breakdown	224
10.11 Piezoelectricity	225
10.12 Ferroelectrics	229
10.13 Optical fibres	230
10.14 The Xerox process	232
10.15 Liquid crystals	233
<b>Exercises</b>	235
<b>11 Magnetic materials</b>	<b>237</b>
11.1 Introduction	237
11.2 Macroscopic approach	238
11.3 Microscopic theory (phenomenological)	238
11.4 Domains and the hysteresis curve	242
11.5 Soft magnetic materials	246
11.6 Hard magnetic materials (permanent magnets)	249
11.7 Microscopic theory (quantum-mechanical)	253
11.7.1 The Stern–Gerlach experiment	257
11.7.2 Paramagnetism	257
11.7.3 Paramagnetic solids	259
11.7.4 Antiferromagnetism	260
11.7.5 Ferromagnetism	260
11.7.6 Ferrimagnetism	261
11.7.7 Garnets	261
11.7.8 Helimagnetism	261
11.8 Magnetic resonance	262
11.8.1 Paramagnetic resonance	262
11.8.2 Electron spin resonance	262
11.8.3 Ferromagnetic, antiferromagnetic, and ferrimagnetic resonance	262
11.8.4 Nuclear magnetic resonance	262
11.8.5 Cyclotron resonance	263
11.8.6 The quantum Hall effect	264
11.9 Some applications	265
11.9.1 Magnetic bubbles	266
11.9.2 Isolators	268
11.9.3 Sensors	269
11.9.4 Medical imaging	269
11.9.5 Electric motors	269
<b>Exercises</b>	270

<b>12 Lasers</b>	<b>271</b>
12.1 Equilibrium	271
12.2 Two-state systems	272
12.3 Lineshape function	275
12.4 Absorption and amplification	277
12.5 Resonators and conditions of oscillation	278
12.6 Some practical laser systems	279
12.6.1 Solid state lasers	279
12.6.2 The gaseous discharge laser	280
12.6.3 Dye lasers	282
12.6.4 Gasdynamic lasers	283
12.6.5 Excimer lasers	284
12.6.6 Chemical lasers	284
12.7 Semiconductor lasers	284
12.8 Laser modes and control techniques	293
12.8.1 Transverse modes	294
12.8.2 Axial modes	294
12.8.3 Q switching	294
12.8.4 Cavity dumping	295
12.8.5 Mode locking	295
12.9 Parametric oscillators	296
12.10 Optical fibre amplifiers	297
12.11 Masers	299
12.12 Noise	299
12.13 Applications	301
12.13.1 Non-linear optics	301
12.13.2 Spectroscopy	302
12.13.3 Photochemistry	302
12.13.4 Study of rapid events	302
12.13.5 Plasma diagnostics	302
12.13.6 Plasma heating	302
12.13.7 Acoustics	302
12.13.8 Genetics	302
12.13.9 Metrology	302
12.14 The atom laser	307
<b>Exercises</b>	<b>308</b>
<b>13 Optoelectronics</b>	<b>310</b>
13.1 Introduction	310
13.2 Light detectors and light-emitting diodes	311
13.3 Infrared detectors	313
13.4 Electro-optic, photorefractive, and non-linear materials	314
13.5 Volume holography and phase conjugation	315
13.6 Acousto-optic interaction	320
13.7 Integrated optics	323
13.7.1 Waveguides	323
13.7.2 Phase shifter	324
13.7.3 Directional coupler	324
13.7.4 Filters	326
13.8 Spatial light modulators	327
13.9 Non-linear Fabry-Perot cavities	329

## Contents

13.10 Electro-absorption in quantum well structures	333
13.10.1 Excitons	333
13.10.2 Excitons in quantum wells	334
13.10.3 Electro-absorption	335
13.10.4 Applications	336
<b>Exercises</b>	<b>338</b>
<b>14 Superconductivity</b>	<b>341</b>
14.1 Introduction	341
14.2 The effect of a magnetic field	344
14.2.1 The critical magnetic field	344
14.2.2 The Meissner effect	344
14.3 Microscopic theory	345
14.4 Thermodynamic treatment	346
14.5 Surface energy	351
14.6 The Landau–Ginzburg theory	353
14.7 The energy gap	359
14.8 Some applications	363
14.8.1 High-field magnets	363
14.8.2 Switches and memory elements	365
14.8.3 Magnetometers	365
14.8.4 Metrology	366
14.8.5 Suspension systems and motors	366
14.8.6 Radiation detectors	367
14.8.7 Heat valves	367
14.9 High- $T_c$ superconductors	367
<b>Exercises</b>	<b>372</b>
<b>Epilogue</b>	<b>373</b>
<b>Appendix I: Symbols, units, and constants</b>	<b>375</b>
<b>Appendix II: Variational calculus</b>	<b>376</b>
<b>Appendix III: Suggestions for further reading</b>	<b>377</b>
<b>Answers to examples</b>	<b>379</b>
<b>Index</b>	<b>382</b>