

Contents

1	Crystal Binding and Structure.....	1
1.1	Classification of Solids by Binding Forces (B)	2
1.1.1	Molecular Crystals and the van der Waals Forces (B)....	2
1.1.2	Ionic Crystals and Born–Mayer Theory (B)	6
1.1.3	Metals and Wigner–Seitz Theory (B)	9
1.1.4	Valence Crystals and Heitler–London Theory (B)	11
1.1.5	Comment on Hydrogen-Bonded Crystals (B).....	12
1.2	Group Theory and Crystallography	13
1.2.1	Definition and Simple Properties of Groups (AB).....	14
1.2.2	Examples of Solid-State Symmetry Properties (B).....	17
1.2.3	Theorem: No Five-fold Symmetry (B)	20
1.2.4	Some Crystal Structure Terms and Nonderived Facts (B)	22
1.2.5	List of Crystal Systems and Bravais Lattices (B)	23
1.2.6	Schoenflies and International Notation for Point Groups (A)	26
1.2.7	Some Typical Crystal Structures (B)	28
1.2.8	Miller Indices (B).....	31
1.2.9	Bragg and von Laue Diffraction (AB)	31
	Problems	38
2	Lattice Vibrations and Thermal Properties.....	41
2.1	The Born–Oppenheimer Approximation (A)	42
2.2	One-Dimensional Lattices (B).....	47
2.2.1	Classical Two-Atom Lattice with Periodic Boundary Conditions (B).....	48
2.2.2	Classical, Large, Perfect Monatomic Lattice, and Introduction to Brillouin Zones (B).....	51
2.2.3	Specific Heat of Linear Lattice (B).....	61
2.2.4	Classical Diatomic Lattices: Optic and Acoustic Modes (B)	64
2.2.5	Classical Lattice with Defects (B)	70
2.2.6	Quantum-Mechanical Linear Lattice (B)	76

2.3	Three-Dimensional Lattices	85
2.3.1	Direct and Reciprocal Lattices and Pertinent Relations (B).....	85
2.3.2	Quantum-Mechanical Treatment and Classical Calculation of the Dispersion Relation (B).....	87
2.3.3	The Debye Theory of Specific Heat (B).....	92
2.3.4	Anharmonic Terms in The Potential / The Gruneisen Parameter (A).....	99
2.3.5	Wave Propagation in an Elastic Crystalline Continuum (MET, MS).....	103
	Problems.....	108
3	Electrons in Periodic Potentials	113
3.1	Reduction to One-Electron Problem	114
3.1.1	The Variational Principle (B)	114
3.1.2	The Hartree Approximation (B)	115
3.1.3	The Hartree–Fock Approximation (A)	119
3.1.4	Coulomb Correlations and the Many-Electron Problem (A).....	135
3.1.5	Density Functional Approximation (A).....	137
3.2	One-Electron Models	148
3.2.1	The Kronig–Penney Model (B)	148
3.2.2	The Free-Electron or Quasifree-Electron Approximation (B)	158
3.2.3	The Problem of One Electron in a Three-Dimensional Periodic Potential.....	173
3.2.4	Effect of Lattice Defects on Electronic States in Crystals (A)	205
	Problems.....	209
4	The Interaction of Electrons and Lattice Vibrations.....	213
4.1	Particles and Interactions of Solid-state Physics (B).....	213
4.2	The Phonon–Phonon Interaction (B).....	219
4.2.1	Anharmonic Terms in the Hamiltonian (B).....	219
4.2.2	Normal and Umklapp Processes (B).....	220
4.2.3	Comment on Thermal Conductivity (B).....	223
4.2.4	Phononics (EE).....	225
4.3	The Electron–Phonon Interaction.....	225
4.3.1	Form of the Hamiltonian (B).....	226
4.3.2	Rigid-Ion Approximation (B).....	229
4.3.3	The Polaron as a Prototype Quasiparticle (A)	232

4.4	Brief Comments on Electron–Electron Interactions (B).....	242
4.5	The Boltzmann Equation and Electrical Conductivity	244
4.5.1	Derivation of the Boltzmann Differential Equation (B).....	244
4.5.2	Motivation for Solving the Boltzmann Differential Equation (B).....	246
4.5.3	Scattering Processes and Q Details (B).....	247
4.5.4	The Relaxation-Time Approximate Solution of the Boltzmann Equation for Metals (B).....	251
4.6	Transport Coefficients	254
4.6.1	The Electrical Conductivity (B).....	254
4.6.2	The Peltier Coefficient (B).....	254
4.6.3	The Thermal Conductivity (B).....	255
4.6.4	The Thermoelectric Power (B)	255
4.6.5	Kelvin’s Theorem (B).....	256
4.6.6	Transport and Material Properties in Composites (MET, MS).....	257
	Problems	263

5 Metals, Alloys, and the Fermi Surface 267

5.1	Fermi Surface (B).....	267
5.1.1	Empty Lattice (B)	268
5.1.2	Exercises (B).....	269
5.2	The Fermi Surface in Real Metals (B).....	273
5.2.1	The Alkali Metals (B).....	273
5.2.2	Hydrogen Metal (B).....	273
5.2.3	The Alkaline Earth Metals (B).....	273
5.2.4	The Noble Metals (B)	273
5.3	Experiments Related to the Fermi Surface (B).....	275
5.4	The de Haas–van Alphen effect (B)	276
5.5	Eutectics (MS, ME).....	280
5.6	Peierls Instability of Linear Metals (B)	281
5.6.1	Relation to Charge Density Waves (A).....	284
5.6.2	Spin Density Waves (A)	285
5.7	Heavy Fermion Systems (A)	285
5.8	Electromigration (EE, MS).....	286
5.9	White Dwarfs and Chandrasekhar’s Limit (A).....	288
5.9.1	Gravitational Self-Energy (A).....	289
5.9.2	Idealized Model of a White Dwarf (A).....	289
5.10	Some Famous Metals and Alloys (B, MET).....	292
	Problems	293

6	Semiconductors	295
6.1	Electron Motion	298
6.1.1	Calculation of Electron and Hole Concentration (B).....	298
6.1.2	Equation of Motion of Electrons in Energy Bands (B)...	304
6.1.3	Concept of Hole Conduction (B).....	307
6.1.4	Conductivity and Mobility in Semiconductors (B).....	309
6.1.5	Drift of Carriers in Electric and Magnetic Fields: The Hall Effect (B).....	311
6.1.6	Cyclotron Resonance (A)	313
6.2	Examples of Semiconductors	320
6.2.1	Models of Band Structure for Si, Ge and II-VI and III-V Materials (A).....	320
6.2.2	Comments about GaN (A)	326
6.3	Semiconductor Device Physics	327
6.3.1	Crystal Growth of Semiconductors (EE, MET, MS).....	327
6.3.2	Gunn Effect (EE).....	328
6.3.3	<i>pn</i> -Junctions (EE)	330
6.3.4	Depletion Width, Varactors, and Graded Junctions (EE).....	333
6.3.5	Metal Semiconductor Junctions — the Schottky Barrier (EE)	336
6.3.6	Semiconductor Surface States and Passivation (EE)	337
6.3.7	Surfaces Under Bias Voltage (EE)	339
6.3.8	Inhomogeneous Semiconductors Not in Equilibrium (EE)	340
6.3.9	Solar Cells (EE).....	346
6.3.10	Transistors (EE).....	352
6.3.11	Charge-Coupled Devices (CCD) (EE).....	353
	Problems.....	353
 7	 Magnetism, Magnons, and Magnetic Resonance	 355
7.1	Types of Magnetism.....	356
7.1.1	Diamagnetism of the Core Electrons (B).....	356
7.1.2	Paramagnetism of Valence Electrons (B).....	357
7.1.3	Ordered Magnetic Systems (B)	360
7.2	Origin and Consequences of Magnetic Order	373
7.2.1	Heisenberg Hamiltonian	373
7.2.2	Magnetic Anisotropy and Magnetostatic Interactions (A).....	385
7.2.3	Spin Waves and Magnons (B).....	390
7.2.4	Band Ferromagnetism (B)	407
7.2.5	Magnetic Phase Transitions (A)	416

7.3	Magnetic Domains and Magnetic Materials (B).....	422
7.3.1	Origin of Domains and General Comments (B).....	422
7.3.2	Magnetic Materials (EE, MS)	432
7.3.3	Nanomagnetism (EE, MS)	434
7.4	Magnetic Resonance and Crystal Field Theory	435
7.4.1	Simple Ideas About Magnetic Resonance (B)	435
7.4.2	A Classical Picture of Resonance (B)	436
7.4.3	The Bloch Equations and Magnetic Resonance (B).....	439
7.4.4	Crystal Field Theory and Related Topics (B)	445
7.5	Brief Mention of Other Topics	453
7.5.1	Spintronics or Magnetoelectronics (EE)	453
7.5.2	The Kondo Effect (A)	457
7.5.3	Spin Glass (A).....	458
7.5.4	Solitons (A, EE).....	460
	Problems	461

8 Superconductivity..... 463

8.1	Introduction and Some Experiments (B)	463
8.1.1	Ultrasonic Attenuation (B).....	467
8.1.2	Electron Tunneling (B)	467
8.1.3	Infrared Absorption (B)	467
8.1.4	Flux Quantization (B)	467
8.1.5	Nuclear Spin Relaxation (B).....	468
8.1.6	Thermal Conductivity (B).....	468
8.2	The London and Ginzburg–Landau Equations (B).....	469
8.2.1	The Coherence Length (B).....	471
8.2.2	Flux Quantization and Fluxoids (B).....	475
8.2.3	Order of Magnitude for Coherence Length (B)	476
8.3	Tunneling (B, EE)	478
8.3.1	Single-Particle or Giaever Tunneling.....	478
8.3.2	Josephson Junction Tunneling	479
8.4	SQUID: Superconducting Quantum Interference (EE)	483
8.4.1	Questions and Answers (B)	485
8.5	The Theory of Superconductivity (A)	486
8.5.1	Assumed Second Quantized Hamiltonian for Electrons and Phonons in Interaction (A).....	486
8.5.2	Elimination of Phonon Variables and Separation of Electron–Electron Attraction Term Due to Virtual Exchange of Phonons (A).....	490
8.5.3	Cooper Pairs and the BCS Hamiltonian (A)	494
8.5.4	Remarks on the Nambu Formalism and Strong Coupling Superconductivity (A).....	504

8.6	Magnesium Diboride (EE, MS, MET)	505
8.7	Heavy-Electron Superconductors (EE, MS, MET)	506
8.8	High-Temperature Superconductors (EE, MS, MET)	506
8.9	Summary Comments on Superconductivity (B)	509
	Problems	512
9	Dielectrics and Ferroelectrics	513
9.1	The Four Types of Dielectric Behavior (B)	513
9.2	Electronic Polarization and the Dielectric Constant (B)	514
9.3	Ferroelectric Crystals (B)	520
9.3.1	Thermodynamics of Ferroelectricity by Landau Theory (B)	521
9.3.2	Further Comment on the Ferroelectric Transition (B, ME)	524
9.3.3	One-Dimensional Model of the Soft Mode of Ferroelectric Transitions (A)	525
9.4	Dielectric Screening and Plasma Oscillations (B)	529
9.4.1	Helicons (EE)	531
9.4.2	Alfvén Waves (EE)	533
9.4.3	Plasmonics (EE)	534
9.5	Free-Electron Screening	534
9.5.1	Introduction (B)	534
9.5.2	The Thomas–Fermi and Debye–Huckel Methods (A, EE)	535
9.5.3	The Lindhard Theory of Screening (A)	538
	Problems	543
10	Optical Properties of Solids	545
10.1	Introduction (B)	545
10.2	Macroscopic Properties (B)	546
10.2.1	Kronig–Kramers Relations (A)	550
10.3	Absorption of Electromagnetic Radiation–General (B)	552
10.4	Direct and Indirect Absorption Coefficients (B)	553
10.5	Oscillator Strengths and Sum Rules (A)	560
10.6	Critical Points and Joint Density of States (A)	561
10.7	Exciton Absorption (A)	562
10.8	Imperfections (B, MS, MET)	563
10.9	Optical Properties of Metals (B, EE, MS)	565
10.10	Lattice Absorption, Reststrahlen, and Polaritons (B)	571
10.10.1	General Results (A)	571
10.10.2	Summary of the Properties of $\epsilon(q, \omega)$ (B)	578
10.10.3	Summary of Absorption Processes: General Equations (B)	579

10.11 Optical Emission, Optical Scattering and Photoemission (B)	580
10.11.1 Emission (B)	580
10.11.2 Einstein A and B Coefficients (B, EE, MS)	581
10.11.3 Raman and Brillouin Scattering (B, MS)	582
10.11.4 Optical Lattices (A, B)	584
10.11.5 Photonics (EE)	584
10.11.6 Negative Index of Refraction (EE)	585
10.12 Magneto-Optic Effects: The Faraday Effect (B, EE, MS)	587
Problems	589
 11 Defects in Solids	591
11.1 Summary About Important Defects (B)	591
11.2 Shallow and Deep Impurity Levels in Semiconductors (EE)	594
11.3 Effective Mass Theory, Shallow Defects, and Superlattices (A) ...	595
11.3.1 Envelope Functions (A)	595
11.3.2 First Approximation (A)	596
11.3.3 Second Approximation (A)	597
11.4 Color Centers (B)	600
11.5 Diffusion (MET, MS)	602
11.6 Edge and Screw Dislocation (MET, MS)	603
11.7 Thermionic Emission (B)	605
11.8 Cold-Field Emission (B)	608
11.9 Microgravity (MS)	610
Problems	611
 12 Current Topics in Solid Condensed-Matter Physics	613
12.1 Surface Reconstruction (MET, MS)	614
12.2 Some Surface Characterization Techniques (MET, MS, EE)	615
12.3 Molecular Beam Epitaxy (MET, MS)	617
12.4 Heterostructures and Quantum Wells	618
12.5 Quantum Structures and Single-Electron Devices (EE)	619
12.5.1 Coulomb Blockade (EE)	620
12.5.2 Tunneling and the Landauer Equation (EE)	623
12.6 Superlattices, Bloch Oscillators, Stark–Wannier Ladders	626
12.6.1 Applications of Superlattices and Related Nanostructures (EE)	629
12.7 Classical and Quantum Hall Effect (A)	631
12.7.1 Classical Hall Effect – CHE (A)	631
12.7.2 The Quantum Mechanics of Electrons in a Magnetic Field: The Landau Gauge (A)	634
12.7.3 Quantum Hall Effect: General Comments (A)	636
12.8 Carbon – Nanotubes and Fullerene Nanotechnology (EE)	640

12.9	Amorphous Semiconductors and the Mobility Edge (EE)	642
12.9.1	Hopping Conductivity (EE).....	642
12.10	Amorphous Magnets (MET, MS)	644
12.11	Soft Condensed Matter (MET, MS).....	644
12.11.1	General Comments	644
12.11.2	Liquid Crystals (MET, MS).....	645
12.11.3	Polymers and Rubbers (MET, MS)	645
	Problems.....	648

Appendices	651
A Units.....	651
B Normal Coordinates	653
C Derivations of Bloch’s Theorem	657
C.1 Simple One-Dimensional Derivation~	657
C.2 Simple Derivation in Three Dimensions	660
C.3 Derivation of Bloch’s Theorem by Group Theory	661
D Density Matrices and Thermodynamics.....	662
E Time-Dependent Perturbation Theory.....	663
F Derivation of The Spin-Orbit Term From Dirac’s Equation.....	664
G The Second Quantization Notation for Fermions and Bosons	666
G.1 Bose Particles	666
G.2 Fermi Particles.....	668
H The Many-Body Problem.....	669
H.1 Propagators	670
H.2 Green Functions.....	671
H.3 Feynman Diagrams.....	671
H.4 Definitions	671
H.5 Diagrams and the Hartree and Hartree–Fock Approximations	672
H.6 The Dyson Equation	675
I Brief Summary of Solid-State Physics.....	676
J Folk Theorems	690
K Handy Mathematical Results	694
L Condensed Matter Nobel Prize Winners (in Physics or Chemistry).....	696
M Problem Solutions	700
M.1 Chapter 1 Solutions	700
M.2 Chapter 2 Solutions	708
M.3 Chapter 3 Solutions	727
M.4 Chapter 4 Solutions	733
M.5 Chapter 5 Solutions	739
M.6 Chapter 6 Solutions	744
M.7 Chapter 7 Solutions	750

M.8	Chapter 8 Solutions.....	760
M.9	Chapter 9 Solutions.....	761
M.10	Chapter 10 Solutions.....	765
M.11	Chapter 11 Solutions.....	772
M.12	Chapter 12 Solutions.....	776
M.13	Appendix B Solutions.....	781

Bibliography **783**

Chapter 1	783
Chapter 2	784
Chapter 3	786
Chapter 4	788
Chapter 5	789
Chapter 6	791
Chapter 7	793
Chapter 8	795
Chapter 9	797
Chapter 10	798
Chapter 11	799
Chapter 12	800
Appendices	804
Subject References	805
Further Reading	808

Index **813**