

James D. Patterson
Bernard C. Bailey

Solid-State Physics

Introduction to the Theory



Springer

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)	69
2.2.6	Quantum-Mechanical Linear Lattice (B)	75

2.3	Three-Dimensional Lattices	84
2.3.1	Direct and Reciprocal Lattices and Pertinent Relations (B)	84
2.3.2	Quantum-Mechanical Treatment and Classical Calculation of the Dispersion Relation (B)	86
2.3.3	The Debye Theory of Specific Heat (B).....	91
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).....	102
	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
4.3	The Electron–Phonon Interaction	225
4.3.1	Form of the Hamiltonian (B).....	225
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.....	253
4.6.1	The Electrical Conductivity (B).....	254
4.6.2	The Peltier Coefficient (B)	254
4.6.3	The Thermal Conductivity (B)	254
4.6.4	The Thermoelectric Power (B).....	255
4.6.5	Kelvin's Theorem (B).....	255
4.6.6	Transport and Material Properties in Composites (MET, MS)	256
	Problems.....	263
5	Metals, Alloys, and the Fermi Surface	265
5.1	Fermi Surface (B).....	265
5.1.1	Empty Lattice (B)	266
5.1.2	Exercises (B)	267
5.2	The Fermi Surface in Real Metals (B)	271
5.2.1	The Alkali Metals (B).....	271
5.2.2	Hydrogen Metal (B)	271
5.2.3	The Alkaline Earth Metals (B)	271
5.2.4	The Noble Metals (B)	271
5.3	Experiments Related to the Fermi Surface (B).....	273
5.4	The de Haas–van Alphen effect (B)	274
5.5	Eutectics (MS, ME).....	278
5.6	Peierls Instability of Linear Metals (B)	279
5.6.1	Relation to Charge Density Waves (A)	282
5.6.2	Spin Density Waves (A)	283
5.7	Heavy Fermion Systems (A)	283
5.8	Electromigration (EE, MS)	284
5.9	White Dwarfs and Chandrasekhar's Limit (A)	286
5.9.1	Gravitational Self-Energy (A)	287
5.9.2	Idealized Model of a White Dwarf (A).....	287
5.10	Some Famous Metals and Alloys (B, MET)	290
	Problems.....	291

6	Semiconductors	293
6.1	Electron Motion	296
6.1.1	Calculation of Electron and Hole Concentration (B).....	296
6.1.2	Equation of Motion of Electrons in Energy Bands (B) ...	302
6.1.3	Concept of Hole Conduction (B).....	305
6.1.4	Conductivity and Mobility in Semiconductors (B)	307
6.1.5	Drift of Carriers in Electric and Magnetic Fields: The Hall Effect (B).....	309
6.1.6	Cyclotron Resonance (A).....	311
6.2	Examples of Semiconductors	319
6.2.1	Models of Band Structure for Si, Ge and II-VI and III-V Materials (A)	319
6.2.2	Comments about GaN (A).....	324
6.3	Semiconductor Device Physics	325
6.3.1	Crystal Growth of Semiconductors (EE, MET, MS).....	325
6.3.2	Gunn Effect (EE).....	326
6.3.3	<i>pn</i> -Junctions (EE).....	328
6.3.4	Depletion Width, Varactors, and Graded Junctions (EE)	331
6.3.5	Metal Semiconductor Junctions — the Schottky Barrier (EE)	334
6.3.6	Semiconductor Surface States and Passivation (EE).....	335
6.3.7	Surfaces Under Bias Voltage (EE)	337
6.3.8	Inhomogeneous Semiconductors Not in Equilibrium (EE)	338
6.3.9	Solar Cells (EE).....	344
6.3.10	Transistors (EE).....	350
6.3.11	Charge-Coupled Devices (CCD) (EE)	350
	Problems.....	351
7	Magnetism, Magnons, and Magnetic Resonance	353
7.1	Types of Magnetism.....	354
7.1.1	Diamagnetism of the Core Electrons (B).....	354
7.1.2	Paramagnetism of Valence Electrons (B).....	355
7.1.3	Ordered Magnetic Systems (B)	358
7.2	Origin and Consequences of Magnetic Order	371
7.2.1	Heisenberg Hamiltonian.....	371
7.2.2	Magnetic Anisotropy and Magnetostatic Interactions (A).....	383
7.2.3	Spin Waves and Magnons (B).....	388
7.2.4	Band Ferromagnetism (B)	405
7.2.5	Magnetic Phase Transitions (A)	414
7.3	Magnetic Domains and Magnetic Materials (B)	420
7.3.1	Origin of Domains and General Comments (B).....	420
7.3.2	Magnetic Materials (EE, MS).....	430

7.4	Magnetic Resonance and Crystal Field Theory.....	432
7.4.1	Simple Ideas About Magnetic Resonance (B).....	432
7.4.2	A Classical Picture of Resonance (B).....	433
7.4.3	The Bloch Equations and Magnetic Resonance (B).....	436
7.4.4	Crystal Field Theory and Related Topics (B).....	442
7.5	Brief Mention of Other Topics.....	450
7.5.1	Spintronics or Magnetoelectronics (EE).....	450
7.5.2	The Kondo Effect (A).....	453
7.5.3	Spin Glass (A)	454
7.5.4	Solitons (A, EE).....	456
	Problems.....	457
8	Superconductivity	459
8.1	Introduction and Some Experiments (B).....	459
8.1.1	Ultrasonic Attenuation (B)	463
8.1.2	Electron Tunneling (B).....	463
8.1.3	Infrared Absorption (B)	463
8.1.4	Flux Quantization (B).....	463
8.1.5	Nuclear Spin Relaxation (B).....	463
8.1.6	Thermal Conductivity (B)	464
8.2	The London and Ginzburg–Landau Equations (B)	465
8.2.1	The Coherence Length (B)	467
8.2.2	Flux Quantization and Fluxoids (B)	471
8.2.3	Order of Magnitude for Coherence Length (B)	472
8.3	Tunneling (B, EE)	473
8.3.1	Single-Particle or Giaever Tunneling	473
8.3.2	Josephson Junction Tunneling	475
8.4	SQUID: Superconducting Quantum Interference (EE)	479
8.4.1	Questions and Answers (B)	481
8.5	The Theory of Superconductivity (A)	482
8.5.1	Assumed Second Quantized Hamiltonian for Electrons and Phonons in Interaction (A).....	482
8.5.2	Elimination of Phonon Variables and Separation of Electron–Electron Attraction Term Due to Virtual Exchange of Phonons (A)	486
8.5.3	Cooper Pairs and the BCS Hamiltonian (A)	489
8.5.4	Remarks on the Nambu Formalism and Strong Coupling Superconductivity (A).....	500
8.6	Magnesium Diboride (EE, MS, MET)	501
8.7	Heavy-Electron Superconductors (EE, MS, MET)	501
8.8	High-Temperature Superconductors (EE, MS, MET).....	502
8.9	Summary Comments on Superconductivity (B).....	504
	Problems.....	507

9	Dielectrics and Ferroelectrics	509
9.1	The Four Types of Dielectric Behavior (B)	509
9.2	Electronic Polarization and the Dielectric Constant (B)	510
9.3	Ferroelectric Crystals (B).....	516
9.3.1	Thermodynamics of Ferroelectricity by Landau Theory (B)	518
9.3.2	Further Comment on the Ferroelectric Transition (B, ME).....	520
9.3.3	One-Dimensional Model of the Soft Mode of Ferroelectric Transitions (A).....	521
9.4	Dielectric Screening and Plasma Oscillations (B)	525
9.4.1	Helicons (EE)	527
9.4.2	Alfvén Waves (EE)	529
9.5	Free-Electron Screening.....	531
9.5.1	Introduction (B)	531
9.5.2	The Thomas–Fermi and Debye–Hückel Methods (A, EE)	531
9.5.3	The Lindhard Theory of Screening (A).....	535
	Problems.....	540
10	Optical Properties of Solids.....	543
10.1	Introduction (B)	543
10.2	Macroscopic Properties (B).....	544
10.2.1	Kronig–Kramers Relations (A)	548
10.3	Absorption of Electromagnetic Radiation–General (B)	550
10.4	Direct and Indirect Absorption Coefficients (B).....	551
10.5	Oscillator Strengths and Sum Rules (A)	558
10.6	Critical Points and Joint Density of States (A).....	559
10.7	Exciton Absorption (A).....	560
10.8	Imperfections (B, MS, MET)	561
10.9	Optical Properties of Metals (B, EE, MS).....	563
10.10	Lattice Absorption, Restrahlen, and Polaritons (B)	569
10.10.1	General Results (A)	569
10.10.2	Summary of the Properties of $\epsilon(q, \omega)$ (B).....	576
10.10.3	Summary of Absorption Processes: General Equations (B)	577
10.11	Optical Emission, Optical Scattering and Photoemission (B).....	578
10.11.1	Emission (B).....	578
10.11.2	Einstein A and B Coefficients (B, EE, MS)	579
10.11.3	Raman and Brillouin Scattering (B, MS)	580
10.12	Magneto-Optic Effects: The Faraday Effect (B, EE, MS)	582
	Problems.....	585

11 Defects in Solids.....	587
11.1 Summary About Important Defects (B)	587
11.2 Shallow and Deep Impurity Levels in Semiconductors (EE).....	590
11.3 Effective Mass Theory, Shallow Defects, and Superlattices (A) ...	591
11.3.1 Envelope Functions (A).....	591
11.3.2 First Approximation (A).....	592
11.3.3 Second Approximation (A)	593
11.4 Color Centers (B)	596
11.5 Diffusion (MET, MS).....	598
11.6 Edge and Screw Dislocation (MET, MS).....	599
11.7 Thermionic Emission (B)	601
11.8 Cold-Field Emission (B)	604
11.9 Microgravity (MS)	606
Problems.....	607
12 Current Topics in Solid Condensed–Matter Physics.....	609
12.1 Surface Reconstruction (MET, MS).....	610
12.2 Some Surface Characterization Techniques (MET, MS, EE)	611
12.3 Molecular Beam Epitaxy (MET, MS).....	613
12.4 Heterostructures and Quantum Wells.....	614
12.5 Quantum Structures and Single-Electron Devices (EE).....	615
12.5.1 Coulomb Blockade (EE).....	616
12.5.2 Tunneling and the Landauer Equation (EE)	619
12.6 Superlattices, Bloch Oscillators, Stark–Wannier Ladders.....	622
12.6.1 Applications of Superlattices and Related Nanostructures (EE)	625
12.7 Classical and Quantum Hall Effect (A).....	627
12.7.1 Classical Hall Effect – CHE (A).....	627
12.7.2 The Quantum Mechanics of Electrons in a Magnetic Field: The Landau Gauge (A)	630
12.7.3 Quantum Hall Effect: General Comments (A)	632
12.8 Carbon – Nanotubes and Fullerene Nanotechnology (EE).....	636
12.9 Amorphous Semiconductors and the Mobility Edge (EE)	637
12.9.1 Hopping Conductivity (EE).....	638
12.10 Amorphous Magnets (MET, MS)	639
12.11 Soft Condensed Matter (MET, MS).....	640
12.11.1 General Comments	640
12.11.2 Liquid Crystals (MET, MS).....	640
12.11.3 Polymers and Rubbers (MET, MS)	641
Problems.....	644

Appendices	647
A Units	647
B Normal Coordinates.....	649
C Derivations of Bloch's Theorem	652
C.1 Simple One-Dimensional Derivation	652
C.2 Simple Derivation in Three Dimensions	655
C.3 Derivation of Bloch's Theorem by Group Theory	656
D Density Matrices and Thermodynamics.....	657
E Time-Dependent Perturbation Theory	658
F Derivation of The Spin-Orbit Term From Dirac's Equation.....	660
G The Second Quantization Notation for Fermions and Bosons	662
G.1 Bose Particles	662
G.2 Fermi Particles.....	663
H The Many-Body Problem.....	665
H.1 Propagators.....	666
H.2 Green Functions	666
H.3 Feynman Diagrams.....	667
H.4 Definitions	667
H.5 Diagrams and the Hartree and Hartree–Fock Approximations	668
H.6 The Dyson Equation.....	671
 Bibliography.....	 673
Chapter 1	673
Chapter 2	674
Chapter 3	676
Chapter 4	678
Chapter 5	679
Chapter 6	681
Chapter 7	683
Chapter 8	685
Chapter 9	687
Chapter 10	688
Chapter 11	689
Chapter 12	690
Appendices	694
Subject References	695
Further Reading.....	698
 Index	 703