

Contents

CHAPTER 1: CRYSTAL STRUCTURE	1
Periodic Array of Atoms	3
Lattice Translation Vectors	4
Basis and the Crystal Structure	5
Primitive Lattice Cell	6
Fundamental Types of Lattices	6
Two-Dimensional Lattice Types	8
Three-Dimensional Lattice Types	9
Index Systems for Crystal Planes	11
Simple Crystal Structures	13
Sodium Chloride Structure	13
Cesium Chloride Structure	14
Hexagonal Close-Packed Structure (hcp)	15
Diamond Structure	16
Cubic Zinc Sulfide Structure	17
Direct Imaging of Atomic Structure	18
Nonideal Crystal Structures	18
Random Stacking and Polytypism	19
Crystal Structure Data	19
Summary	22
Problems	22
CHAPTER 2: WAVE DIFFRACTION AND THE RECIPROCAL LATTICE	23
Diffraction of Waves by Crystals	25
Bragg Law	25
Scattered Wave Amplitude	26
Fourier Analysis	27
Reciprocal Lattice Vectors	29
Diffraction Conditions	30
Laue Equations	32
Brillouin Zones	33
Reciprocal Lattice to sc Lattice	34
Reciprocal Lattice to bcc Lattice	36
Reciprocal Lattice to fcc Lattice	37

Fourier Analysis of the Basis	39
Structure Factor of the bcc Lattice	40
Structure factor of the fcc Lattice	40
Atomic Form Factor	41
Summary	43
Problems	43

CHAPTER 3: CRYSTAL BINDING AND ELASTIC CONSTANTS 47

Crystals of Inert Gases	49
Van der Waals—London Interaction	53
Repulsive Interaction	56
Equilibrium Lattice Constants	58
Cohesive Energy	59
Ionic Crystals	60
Electrostatic or Madelung Energy	60
Evaluation of the Madelung Constant	64
Covalent Crystals	67
Metals	69
Hydrogen Bonds	70
Atomic Radii	70
Ionic Crystal Radii	72
Analysis of Elastic Strains	73
Dilation	75
Stress Components	75
Elastic Compliance and Stiffness	
Constants	77
Elastic Energy Density	77
Elastic Stiffness Constants of Cubic Crystals	78
Bulk Modulus and Compressibility	80
Elastic Waves in Cubic Crystals	80
Waves in the [100] Direction	81
Waves in the [110] Direction	82
Summary	85
Problems	85

CHAPTER 4: PHONONS I. CRYSTAL VIBRATIONS 89

Vibrations of Crystals with Monatomic Basis	91
First Brillouin Zone	93
Group Velocity	94

Long Wavelength Limit	94
Derivation of Force Constants from Experiment	94
Two Atoms per Primitive Basis	95
Quantization of Elastic Waves	99
Phonon Momentum	100
Inelastic Scattering by Phonons	100
Summary	102
Problems	102
CHAPTER 5: PHONONS 11. THERMAL PROPERTIES	105
Phonon Heat Capacity	107
Planck Distribution	107
Normal Mode Enumeration	108
Density of States in One Dimension	108
Density of States in Three Dimensions	111
Debye Model for Density of States	112
Debye T^3 Law	114
Einstein Model of the Density of States	114
General Result for $D(w)$	117
Anharmonic Crystal Interactions	119
Thermal Expansion	120
Thermal Conductivity	121
Thermal Resistivity of Phonon Gas	123
Umklapp Processes	125
Imperfecions	126
Problems	128
CHAPTER 6: FREE ELECTRON FERMI GAS	131
Energy Levels in One Dimension	134
Effect of Temperature on the Fermi-Dirac Distribution	136
Free Electron Gas in Three Dimensions	137
Heat Capacity of the Electron Gas	141
Experimental Heat Capacity of Metals	145
Heavy Fermions	147
Electrical Conductivity and Ohm's Law	147
Experimental Electrical Resistivity of Metals	148
Umklapp Scattering	151

Motion in Magnetic Fields	152
Hall Effect	153
Thermal Conductivity of Metals	156
Ratio of Thermal to Electrical Conductivity	156
Problems	157

CHAPTER 7: ENERGY BANDS **161**

Nearly Free Electron Model	164
Origin of the Energy Gap	165
Magnitude of the Energy Gap	167
Bloch Functions	167
Kronig-Penney Model	168
Wave Equation of Electron in a	
Periodic Potential	169
Restatement of the Bloch Theorem	173
Crystal Momentum of an Electron	173
Solution of the Central Equation	174
Kronig-Penney Model in Reciprocal Space	174
Empty Lattice Approximation	176
Approximate Solution Near a Zone Boundary	177
Number of Orbitals in a Band	180
Metals and Insulators	181
Summary	182
Problems	182

CHAPTER 8: SEMICONDUCTOR CRYSTALS **185**

Band Gap	187
Equations of Motion	191
Physical Derivation of $\hbar\dot{\mathbf{k}} = \mathbf{F}$	193
Holes	194
Effective Mass	197
Physical Interpretation of the Effective Mass	198
Effective Masses in Semiconductors	200
Silicon and Germanium	202
Intrinsic Carrier Concentration	205
Intrinsic Mobility	208
Impurity Conductivity	209
Donor States	209
Acceptor States	211
Thermal Ionization of Donors and Acceptors	213

Thermoelectric Effects	214
Semimetals	215
Superlattices	216
Bloch Oscillator	217
Zener Tunneling	217
Summary	217
Problems	218

CHAPTER 9: FERMION SURFACES AND METALS 221

Reduced Zone Scheme	223
Periodic Zone Scheme	225
Construction of Fermi Surfaces	226
Nearly Free Electrons	228
Electron Orbits, Hole Orbits, and Open Orbits	230
Calculation of Energy Bands	232
Tight Binding Method of Energy Bands	232
Wigner-Seitz Method	236
Cohesive Energy	237
Pseudopotential Methods	239
Experimental Methods in Fermi Surface Studies	242
Quantization of Orbits in a Magnetic Field	242
De Haas-van Alphen Effect	244
Extremal Orbits	248
Fermi Surface of Copper	249
Magnetic Breakdown	251
Summary	252
Problems	252

CHAPTER 10: SUPERCONDUCTIVITY 257

Experimental Survey	259
Occurrence of Superconductivity	260
Destruction of Superconductivity of Magnetic Fields	262
Meissner Effect	262
Heat Capacity	264
Energy Gap	266
Microwave and Infrared Properties	268
Isotope Effect	269
Theoretical Survey	270
Thermodynamics of the Superconducting Transition	270
London Equation	273

Coherence Length	276
BCS Theory of Superconductivity	277
BCS Ground State	278
Flux Quantization in a Superconducting Ring	279
Duration of Persistent Currents	282
Type II Superconductors	283
Vortex State	284
Estimation of H_{c1} and H_{c2}	284
Single Particle Tunneling	287
Josephson Superconductor Tunneling	289
Dc Josephson Effect	289
Ac Josephson Effect	290
Macroscopic Quantum Interference	292
High-Temperature Superconductors	293
Summary	294
Problems	294
Reference	296

CHAPTER 11: DIAMAGNETISM AND PARAMAGNETISM 297

Langevin Diamagnetism Equation	299
Quantum Theory of Diamagnetism of Mononuclear Systems	301
Paramagnetism	302
Quantum Theory of Paramagnetism	302
Rare Earth Ions	305
Hund Rules	306
Iron Group Ions	307
Crystal Field Splitting	307
Quenching of the Orbital Angular Momentum	308
Spectroscopic Splitting Factor	311
Van Vleck Temperature-Independent Paramagnetism	311
Cooling by Isentropic Demagnetization	312
Nuclear Demagnetization	314
Paramagnetic Susceptibility of Conduction Electrons	315
Summary	317
Problems	318

CHAPTER 12: FERROMAGNETISM AND ANTIFERROMAGNETISM 321

Ferromagnetic Order	323
Curie Point and the Exchange Integral	323

Temperature Dependence of the Saturation Magnetization	326
Saturation Magnetization at Absolute Zero	328
Magnons	330
Quantization of Spin Waves	333
Thermal Excitation of Magnons	334
Neutron Magnetic Scattering	335
Ferrimagnetic Order	336
Curie Temperature and Susceptibility of Ferrimagnets	338
Iron Garnets	339
Antiferromagnetic Order	340
Susceptibility Below the Néel Temperature	343
Antiferromagnetic Magnons	344
Ferromagnetic Domains	346
Anisotropy Energy	348
Transition Region between Domains	349
Origin of Domains	351
Coercivity and Hysteresis	352
Single Domain Particles	354
Geomagnetism and Biomagnetism	355
Magnetic Force Microscopy	355
Summary	356
Problems	357

CHAPTER 13: MAGNETIC RESONANCE 361

Nuclear Magnetic Resonance	363
Equations of Motion	366
Line Width	370
Motional Narrowing	371
Hyperfine Splitting	373
Examples: Paramagnetic Point Defects	375
F Centers in Alkali Halides	376
Donor Atoms in Silicon	376
Knight Shift	377
Nuclear Quadrupole Resonance	379
Ferromagnetic Resonance	379
Shape Effects in FMR	380
Spin Wave Resonance	382
Antiferromagnetic Resonance	383

Electron Paramagnetic Resonance	386
Exchange Narrowing	386
Zero-field Splitting	386
Principle of Maser Action	386
Three-Level Maser	388
Lasers	389
Summary	390
Problems	391

CHAPTER 14: PLASMONS, POLARITONS, AND POLARONS 393

Dielectric Function of the Electron Gas	395
Definitions of the Dielectric Function	395
Plasma Optics	396
Dispersion Relation for Electromagnetic Waves	397
Transverse Optical Modes in a Plasma	398
Transparency of Metals in the Ultraviolet	398
Longitudinal Plasma Oscillations	398
Plasmons	401
Electrostatic Screening	403
Screened Coulomb Potential	406
Pseudopotential Component $U(0)$	407
Mott Metal-Insulator Transition	407
Screening and Phonons in Metals	409
Polaritons	410
LST Relation	414
Electron-Electron Interaction	417
Fermi Liquid	417
Electron-Electron Collisions	417
Electron-Phonon Interaction:	
Polarons	420
Peierls Instability of Linear	
Metals	422
Summary	424
Problems	424

CHAPTER 15: OPTICAL PROCESSES AND EXCITONS 427

Optical Reflectance	429
Kramers-Kronig Relations	430
Mathematical Note	432

Example: Conductivity of collisionless Electron Gas	433
Electronic Interband Transitions	434
Excitons	435
Frenkel Excitons	437
Alkali Halides	440
Molecular Crystals	440
Weakly Bound (Mott-Wannier) Excitons	441
Exciton Condensation into Electron-Hole Drops (EHD)	441
Raman Effects in Crystals	444
Electron Spectroscopy with X-Rays	447
Energy Loss of Fast Particles in a Solid	448
Summary	449
Problems	450
CHAPTER 16: DIELECTRICS AND FERROELECTRICS	453
Maxwell Equations	455
Polarization	455
Macroscopic Electric Field	456
Depolarization Field, E_1	458
Local Electric Field at an Atom	460
Lorentz Field, E_2	462
Field of Dipoles Inside Cavity, E_3	462
Dielectric Constant and Polarizability	463
Electronic Polarizability	464
Classical Theory of Electronic Polarizability	466
Structural Phase Transitions	467
Ferroelectric Crystals	467
Classification of Ferroelectric Crystals	469
Displacive Transitions	471
Soft Optical Phonons	473
Landau Theory of the Phase Transition	474
Second-Order Transition	475
First-Order Transition	477
Antiferroelectricity	479
Ferroelectric Domains	479
Piezoelectricity	481
Summary	482
Problems	483

CHAPTER 17: SURFACE AND INTERFACE PHYSICS	487
Reconstruction and Relaxation	489
Surface Crystallography	490
Reflection High-Energy Electron	
Diffraction	493
Surface Electronic Structure	494
Work Function	494
Thermionic Emission	495
Surface States	495
Tangential Surface Transport	497
Magnetoresistance in a Two-Dimensional	
Channel	498
Integral Quantized Hall Effect (IQHE)	499
IQHE in Real Systems	500
Fractional Quantized Hall Effect (FQHE)	503
<i>p-n</i> Junctions	503
Rectification	504
Solar Cells and Photovoltaic Detectors	506
Schottky Barrier	506
Heterostructures	507
<i>n-N</i> Heterojunction	508
Semiconductor Lasers	510
Light-Emitting Diodes	511
Problems	513
CHAPTER 18: NANOSTRUCTURES	515
Imaging Techniques for Nanostructures	519
Electron Microscopy	520
Optical Microscopy	521
Scanning Tunneling Microscopy	523
Atomic Force Microscopy	526
Electronic Structure of 1D Systems	528
One-Dimensional Subbands	528
Spectroscopy of Van Hove Singularities	529
1D Metals — Coulomb Interactions and Lattice	
Coulplings	531
Electrical Transport in 1D	533
Conductance Quantization and the Landauer	
Formula	533
Two Barriers in Series-resonant Tunneling	536
Incoherent Addition and Ohm's Law	538

Localization	539
Voltage Probes and the Buttiker-Landauer Formalism	540
Electronic Structure of 0D Systems	545
Quantized Energy Levels	545
Semiconductor Nanocrystals	545
Metallic Dots	547
Discrete Charge States	549
Electrical Transport in 0D	551
Coulomb Oscillations	551
Spin, Mott Insulators, and the Kondo Effect	554
Cooper Pairing in Superconducting Dots	556
Vibrational and Thermal Properties of Nanostructures	557
Quantized Vibrational Modes	557
Transverse Vibrations	559
Heat Capacity and Thermal Transport	561
Summary	562
Problems	562

CHAPTER 19: NONCRYSTALLINE SOLIDS 565

Diffraction Pattern	567
Monatomic Amorphous Materials	568
Radial Distribution Function	569
Structure of Vitreous Silica, SiO_2	570
Glasses	573
Viscosity and the Hopping Rate	574
Amorphous Ferromagnets	575
Amorphous Semiconductors	577
Low Energy Excitations in Amorphous Solids	578
Heat Capacity Calculation	578
Thermal Conductivity	579
Fiber Optics	581
Rayleigh Attenuation	582
Problems	582

CHAPTER 20: POINT DEFECTS 583

Lattice Vacancies	585
Diffusion	588
Metals	591

Color Centers	592
<i>F</i> Centers	592
Other Centers in Alkali Halides	593
Problems	595
CHAPTER 21: DISLOCATIONS	597
Shear Strength of Single Crystals	599
Slip	600
Dislocations	601
Burgers Vectors	604
Stress Fields of Dislocations	605
Low-angle Grain Boundaries	607
Dislocation Densities	610
Dislocation Multiplication and Slip	611
Strength of Alloys	613
Dislocations and Crystal Growth	615
Whiskers	616
Hardness of Materials	617
Problems	618
CHAPTER 22: ALLOYS	619
General Considerations	621
Substitutional Solid Solutions—	
Hume-Rothery Rules	624
Order-Disorder Transformation	627
Elementary Theory of Order	629
Phase Diagrams	632
Eutectics	632
Transition Metal Alloys	634
Electrical Conductivity	636
Kondo Effect	637
Problems	640
APPENDIX A: TEMPERATURE DEPENDENCE OF THE REFLECTION LINES	641
APPENDIX B: EWALD CALCULATION OF LATTICE SUMS	644
Ewald-Kornfeld Method for Lattice Sums	
for Dipole Arrays	647

APPENDIX C:	QUANTIZATION OF ELASTIC WAVES: PHONONS	648
	Phonon Coordinates	649
	Creation and Annihilation Operators	651
APPENDIX D:	FERMI-DIRAC DISTRIBUTION FUNCTION	652
APPENDIX E:	DERIVATION OF THE $d\mathbf{k}/dt$ EQUATION	655
APPENDIX F:	BOLTZMANN TRANSPORT EQUATION	656
	Particle Diffusion	657
	Classical Distribution	658
	Fermi-Dirac Distribution	659
	Electrical Conductivity	661
APPENDIX G:	VECTOR POTENTIAL, FIELD MOMENTUM, AND GAUGE TRANSFORMATIONS	661
	Lagrangian Equations of Motion	662
	Derivation of the Hamiltonian	663
	Field Momentum	663
	Gauge Transformation	664
	Gauge in the London Equation	665
APPENDIX H:	COOPER PAIRS	665
APPENDIX I:	GINZBURG-LANDAU EQUATION	667
APPENDIX J:	ELECTRON-PHONON COLLISIONS	671
INDEX		675