Complete Solid State Physics

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Contents

1 Crystal Structure

1.1 Core ideas

Crystals are periodic arrangements of atoms described by a lattice plus a basis. Symmetry, unit cells, Bravais lattices, Miller indices, and reciprocal space organize real materials and determine allowed diffraction and band structures.

For review, be able to identify primitive cells, reciprocal vectors, common lattices, and planes from Miller indices. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

1.2 Mathematical spine

$$\boldsymbol{R} = n_1\boldsymbol{a}_1 + n_2\boldsymbol{a}_2 + n_3\boldsymbol{a}_3, \qquad \boldsymbol{a}_i \cdot \boldsymbol{b}_j = 2\pi\delta_{ij}$$

Section summary Crystal periodicity is the starting point of solid-state physics.

2 Wave Diffraction and the Reciprocal Lattice

2.1 Core ideas

Diffraction measures periodic structure through constructive interference. Reciprocal lattice vectors encode allowed momentum transfer. Bragg's law, Laue conditions, structure factors, and Brillouin zones connect scattering patterns to atomic arrangements.

For review, be able to use Bragg and Laue conditions, compute simple structure factors, and interpret Brillouin zones. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

2.2 Mathematical spine

$$\Delta\boldsymbol{k} = \boldsymbol{G}, \qquad 2d\sin\theta = n\lambda, \qquad S_{\boldsymbol{G}} = \sum_j f_j e^{i\boldsymbol{G}\cdot\boldsymbol{r}_j}$$

Section summary Diffraction is a direct probe of reciprocal-lattice structure.

3 Crystal Binding and Elastic Constants

3.1 Core ideas

Solids bind through ionic, covalent, metallic, molecular, and hydrogen-bond interactions. Elastic constants describe the energy cost of strain and connect microscopic bonding to sound speeds and mechanical response.

For review, be able to compare bonding types, use strain and stress tensors, and relate elastic moduli to stability. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

3.2 Mathematical spine

$$u = \frac{1}{2} C_{ijkl} \epsilon_{ij} \epsilon_{kl}, \qquad \sigma_{ij} = C_{ijkl} \epsilon_{kl}$$

Section summary Bonding sets both structure and elasticity.

4 Phonons I: Crystal Vibrations

4.1 Core ideas

Atoms in crystals vibrate collectively as phonons. Normal modes arise from coupled harmonic oscillators; acoustic branches reflect translations, while optical branches occur when the basis has multiple atoms.

For review, be able to derive a simple dispersion relation, distinguish acoustic and optical modes, and interpret phonon momentum. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

4.2 Mathematical spine

$$\omega(k) = 2\sqrt{K/M} \left| \sin \frac{ka}{2} \right|, \qquad E_{\boldsymbol{q},s} = \hbar \omega_{\boldsymbol{q},s} \left(n + \frac{1}{2} \right)$$

Section summary Phonons are quantized normal modes of lattice vibration.

5 Phonons II: Thermal Properties

5.1 Core ideas

Phonons carry heat and determine low-temperature heat capacity. Einstein and Debye models approximate the phonon spectrum; scattering of phonons by defects, boundaries, and other phonons controls thermal conductivity.

For review, be able to derive Debye T^3 law, compare Einstein and Debye models, and estimate thermal conductivity. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

5.2 Mathematical spine

$$C_V \propto T^3 \quad (T \ll \Theta_D), \qquad \kappa \simeq \frac{1}{3} C_V v_s \ell$$

Section summary Lattice thermal properties are phonon thermodynamics and transport.

6 Free Electron Fermi Gas

6.1 Core ideas

Conduction electrons in simple metals are modeled as a Fermi gas. Pauli exclusion creates a Fermi surface and explains degeneracy pressure, small electronic heat capacity, and basic metallic transport.

For review, be able to compute k_F, E_F, density of states, and low-temperature heat capacity. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

6.2 Mathematical spine

$$k_F = (3\pi^2 n)^{1/3}, \qquad E_F = \frac{\hbar^2 k_F^2}{2m}, \qquad C_e = \gamma T$$

Section summary Metal electrons are governed by Fermi statistics.

7 Energy Bands

7.1 Core ideas

Periodic potentials turn free-electron energies into bands separated by gaps. Bloch's theorem labels states by crystal momentum. Band filling explains metals, insulators, and semiconductors.

For review, be able to use Bloch's theorem, interpret band gaps, effective mass, and density of states. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

7.2 Mathematical spine

$$\psi_{n\boldsymbol{k}}(\boldsymbol{r}) = e^{i\boldsymbol{k}\cdot\boldsymbol{r}} u_{n\boldsymbol{k}}(\boldsymbol{r}), \qquad \boldsymbol{v}_n = \frac{1}{\hbar}\nabla_{\boldsymbol{k}} E_n(\boldsymbol{k})$$

Section summary Bands are quantum states shaped by lattice periodicity.

8 Semiconductor Crystals

8.1 Core ideas

Semiconductors have small band gaps and carrier densities controlled by temperature, doping, and illumination. Electrons and holes, effective masses, donor and acceptor levels, p-n junctions, and recombination form the device foundation.

For review, be able to use carrier statistics, distinguish intrinsic and doped regimes, and explain p-n junction depletion. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

8.2 Mathematical spine

$$np = n_i^2, \qquad n_i \propto T^{3/2} e^{-E_g/(2k_B T)}, \qquad E_{\text{donor}} \sim \frac{m^*}{\epsilon_r^2} 13.6\,\text{eV}$$

Section summary Semiconductors are controllable band insulators.

9 Fermi Surfaces and Metals

9.1 Core ideas

The Fermi surface controls metallic response because only nearby states can change occupancy. Its shape determines velocities, effective masses, magnetoresistance, quantum oscillations, and transport anisotropy.

For review, be able to connect Fermi surface geometry to transport, define effective mass, and interpret Hall and quantum oscillation measurements. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

9.2 Mathematical spine

$$\boldsymbol{v}_F = \frac{1}{\hbar}\nabla_{\boldsymbol{k}} E(\boldsymbol{k}), \qquad A_F \frac{\hbar}{eB} = 2\pi\,(n+\gamma)$$

Section summary Metallic behavior is determined by Fermi-surface geometry.

10 Superconductivity

10.1 Core ideas

Superconductors have zero dc resistance, Meissner expulsion, an energy gap, flux quantization, and phase coherence. BCS theory explains pairing from an effective attraction; Ginzburg-Landau theory describes order-parameter physics and vortices.

For review, be able to state Meissner effect, flux quantization, gap scale, type I/II behavior, and the role of Cooper pairs. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

10.2 Mathematical spine

$$\Phi_0 = \frac{h}{2e}, \qquad 2\Delta(0) \approx 3.52 k_B T_c, \qquad \boldsymbol{J}_s \propto |\psi|^2(\hbar\nabla\phi - 2e\boldsymbol{A})$$

Section summary Superconductivity is macroscopic quantum phase coherence of paired electrons.

11 Dielectrics and Ferroelectrics

11.1 Core ideas

Dielectrics polarize under electric fields through electronic, ionic, orientational, and space-charge mechanisms. Ferroelectrics have spontaneous switchable polarization and domain structure, often described by Landau theory.

For review, be able to use susceptibility and permittivity, identify polarization mechanisms, and explain ferroelectric hysteresis. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

11.2 Mathematical spine

$$\boldsymbol{P} = \epsilon_0 \chi_e \boldsymbol{E}, \qquad F(P) = a(T - T_c)P^2 + bP^4 - EP$$

Section summary Dielectric response reflects how charge distributions deform.

12 Paramagnetism, Diamagnetism, and Ferromagnetism

12.1 Core ideas

Magnetism comes from orbital and spin moments plus exchange interactions. Diamagnets weakly oppose fields; paramagnets align with fields; ferromagnets order spontaneously and form domains.

For review, be able to distinguish magnetic responses, use Curie law, explain exchange and spontaneous symmetry breaking. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

12.2 Mathematical spine

$$\chi_{\text{Curie}} = \frac{C}{T}, \qquad H = -\sum_{ij} J_{ij} \boldsymbol{S}_i \cdot \boldsymbol{S}_j$$

Section summary Magnetism is collective behavior of microscopic moments.

13 Nanophysics / Surfaces and Interfaces

13.1 Core ideas

At nanoscale dimensions, surfaces, confinement, disorder, and interfaces dominate. Quantum wells, tunneling, 2D electron gases, surface states, heterostructures, and mesoscopic transport require both band and scattering viewpoints.

For review, be able to estimate confinement energies, use tunneling intuition, and explain why surface-to-volume ratio matters. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

13.2 Mathematical spine

$$\Delta E \sim \frac{\hbar^2 \pi^2}{2mL^2}, \qquad G = \frac{2e^2}{h} \sum_n T_n$$

Section summary Nanoscale solids reveal quantum confinement and interface physics.