UNIVERSITÀ
DEGLI STUDI DI MILANO-BICOCCA

SYLLABUS DEL CORSO

Solid State Physics

2122-1-F5302Q001

Aims

The Course is aimed to the understanding of concepts, methods and models for the physics of perfect and infinite crystalline solids. To this purpose topics are divided in three parts. A first part of the course is devoted to the treatment of simpler phenomena, as described in terms of non-interacting particles (electrons, or phonons), with particular attention in teaching the skill of developing analytical models, which allow to solve complicated problems by ingenious simplifications. The second part includes those phenomenon related to the electrons in the crystal lattice, returning the band structure and transport properties, and also exploits the combination of physical reasoning and mathematical analysis. The third part focuses on more complex phenomena, generated by the interaction among particles, which give rise to significant macroscopic properties of the perfect and infinite solid. In this last part, the focus is placed in the understanding of non-intuitive concepts and the ideal line of reasoning, preferring - also here - the methodological approach rather than the taxonomic one. The complementation of a main text with the material uploaded on the Course site, is one important aspect of the teaching method, that is to acquire the habit of consulting different sources and comparing them critically.

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Part 1
I. Crystal structures and diffraction
II. Lattice dynamics
III. Thermal properties of solids
IV. The free-electron gas

Part 2
V. Electronic bands

VI. Transport of charge and heat by electrons

Part 3
VII. The many-electron problem and the effects of electronic screening
VIII. Magnetic properties of solids
IX. Superconductivity

Detailed program

PART 1

I. Crystal structures and diffraction

- Bravais lattices and relevant crystal structures
- Theory of diffraction and experimental techniques
- Construction of the reciprocal lattice and the Brillouin zones, in particular for FCC, BCC and HCP structures
- Calculation of the distances between high-symmetry points in the Brillouine zone for silicon.

II. Lattice dynamics

- Foundations of lattice dynamics: force constant matrix and its symmetries, dynamical matrix and the equations of motion
- Dynamics of the diatomic linear chain
- Construction and diagonalization of the dynamic matrix for one fcc monatomic: eigenvalues and displacement patterns
- Normal modes, sound waves and elasticity
- Phonons as collective modes and their statistics
- Inelastic scattering and measurement of phonon dispersion by neutron scattering

III. Thermal properties of solids

- Density of vibrational states
- Specific heat in Debye and Einstein models
- Anharmonic potentials and effects: qualitative interpretation to thermal expansion and deviation of the heat capacity from Dulong Petit law
- Thermal expansion and meaning of the Gruneisen parameter
- Thermal conductivity by lattice vibrations

IV. The free-electron gas

- The free-electron gas model
- The Fermi-Dirac statistics of electrons
- Density of states: definition and calculation for 3D, 2D and 1D electron gas. Trend of the chemical potential in T
- Electronic contribution to the specific heat and heavy fermions
- The work function and the thermal emission of electrons: physics and application

PART 2

V. Electronic bands

- Periodic potential, central equation and Bloch states
- Construction of the band diagram for the empty lattice
- Band structure in the nearly-free electron model: opening of the gap at the Brillouin zone borders and its interpretation
- Introduction to the Tight-Binding model (TB)
- Band calculation in the TB model: role of neighbors and atomic basis and hopping integrals
- Construction and diagonalization of the tight binding matrix to first neighbors for silicon
- Interpretation of real bands and their density of states
- Measurement of the dispersion of the bands by angle-resolved electron photoemission

VI. Transport of charge and heat by electrons

- The semiclassic model and motion of electrons in bands due to an electric field
- The effective mass tensor and the concept of positive hole
- Boltzmann equation: balance between the process of drift and the one of scattering
- The relaxation time approximation for scattering processes
- Microscopic mechanisms that rule the scattering of electrons in bands
- The electrical conductivity in metals
- Dependence of electrical conductivity on the temperature
- Heat transport by electrons and the Wiedemann-Franz law
- Thermoelectric effects (Peltier and Seebeck) and applications
- Motion of electrons in weak magnetic fields: magneto-resistance and Hall effect
- Free-electron gas in a magnetic field: Landau levels and their energies
- Motion of electrons in strong magnetic fields: Landau tubes, oscillatory properties and the De Haas-Van Alphen effect

PART 3

VII. The many-electron problem and the effects of electronic screening

- From the many-electron system to the mean-field equation: Hartree equation
- The Hartree-Fock equations and meaning of the exchange energy contribution
- The interacting gas of free electrons
- Foundations of the density functional theory: the Hohenberg and Kohn theorem and the Kohn-Sham equation
- Ground-state properties and elementary excitations
- Cellular methods, the muffin tin potential, and the augmented plane waves
- Orthogonalization of valence states to core states: orthogonalized plane waves and pseudopotentials
- Shallow impurities: energy levels and envelope function
- Electronic screening in the Thomas-Fermi model
- Electronic screening in the perturbative, Lindhard model
- Bonding and crystal structure in simple metals and other solids

VIII. Magnetic properties of solids

- Diamagnetism and paramagnetism in insulating solids
- Pauli paramagnetism and Landau diamagnetism for the gas of free electrons
- Stoner model for band ferromagnetism in metallic solids

- Effect of temperature in the Stoner model, Curie temperature
- Ferromagnetism in insulating solids and the Heisenberg hamiltonian
- Antiferromagnetism and anisotropic magnetic susceptivity
- Excited magnetic states: spin waves and magnons
- Neutron scattering, role of magnons at low temperature, ferromagnetic domains

IX. Superconductivity

- Introduction to superconductivity: Onnes experiment and Meissner-Ochsenfeld effect
- The London and London equations: penetration of currents and magnetic fields
- The thermodynamics of the superconducting phase: free-energy, entropy and heat capacity
- Cooper pairs and instability of the Fermi sea
- Ground state in the Bardeen-Cooper-Schrieffer (BCS) theory
- Existence of the gap, its nature, and definition of the excited states in the BCS theory
- The supercorrent as steady state, critical values of current and magnetic field and Meissner effect in the BCS theory
- Experimental measurements of the gap, its temperature dependence and isotropic effect
- High-Tc superconductors

Prerequisites

Atomic and molecular quantum physics (also provided by a suitable Course inside this curriculum)

Elementary introduction to Materials (beneficial for undergraduates coming from different degrees)

A short course in advanced calculus: complex calculus, special functions, series and transforms

Teaching form

Lessons and practice lessons.

Textbook and teaching resource

MAIN TEXTBOOK:

H. IBACH AND H. LUTH, *Solids State Physics*, Springer Verlag

ADDITIONAL CHAPTERS ARE TAKEN FROM THE FOLLOWING BOOKS, STILL AVAILABLE IN ENGLISH IN THE E-LEARNING PLATFORM OR AVAILABLE FROM THE UNIVERSITY LIBRARY:

N.W ASHCROFT AND N.D. MERMIN, *Solid State Physics*, Saunders College Publishing

F. BASSANI E U. GRASSANO, *Fisica dello Stato Solido*, Casa Editrice Boringhieri

G. GROSSO AND G. PASTORI PARRAVICINI, *Solid state Physics*, Academic Press

A.P. SUTTON, *Electronic Structure of Materials*, Oxford University Press

J.R. HOOK and H.E. Hall, *Solid State Physics*, John Wiley & Sons

S. BLUNDELL, Magnetism in Condensed Matter, Oxford University Press.

Semester

First and second semester at different lesson periodicity. In particular, the lessons will start with the second part of the first semester, so that the basic course in quantum mechanics and the advanced course in calculus can provide most of the subjects necessary to follow this course. The students are therefore warmely invited to attend these two coursed with attention and continuity.

Assessment method

The final examination consists of two stages, that students can eventually take at different times. The first one concerns the topics of the Parts 1 and 2 of the course, and it includes a written mathematical derivation of some physical results. The second one regards the (more complex) topics of the Part 3 of the course, it is fully oral and mainly intended to test the understanding of the effects taking place, quoting - in case deriving - the quantitative results.

During the teaching time, students attending the course will have the possibility of taking the exam splitted in three partials, one for each part of the course. Since this assisted path requires that students study in parallel to lessons, active participation to them is warmely recommended. To further ease the preparation, organize and explain the exam modality and answer any question on the course topics, before each partial exam a meeting with the enrolled students, open to all others, will be scheduled.

Office hours

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