UNIVERSITÀ
DEGLI STUDI DI MILANO-BICOCCA

COURSE SYLLABUS

Solid State Physics

2021-1-F5302Q001

Aims

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 analyses more complex phenomena, generated by the interaction among particles, which give rise to significant macroscopic properties of the perfect and infinite solid. In this 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 some suggested material, uploaded in 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.

Contents

First part

1. REVIEW OF CRYSTAL STRUCTURES AND BRAVAIS LATTICES, IN DIRECT AND RECIPROCAL SPACE
2. LATTICE DYNAMICS IN THREE DIMENSIONS
3. THERMAL PROPERTIES OF SOLIDS IN THE HARMONIC AND THE ANHARMONIC APPROACH
4. FREE AND INDEPENDENT ELECTRON GAS, RELATED THERMAL PROPERTIES
5. FUNDAMENTALS OF ELECTRONIC BANDS AND REALISTIC CASES
6. CHARGE AND HEAT TRANSPORT BY ELECTRONS

Second part

7. CALCULATION OF THE ELECTRONIC BANDS WITH SELFCONSISTENT METHODS

8. ELECTRON SCREENING AND THE STRUCTURAL ENERGY OF METALS
9. PARAMAGNETISM, DIAMAGNETISM AND LANDAU LEVELS
10. FERROMAGNETISM FOR ITINERANT AND LOCALIZED SPINS
11. SUPERCONDUCTIVITY AND THE BCS THEORY

Detailed program

Crystal structures and diffraction

- The Bravais lattices and relevant crystal structures
- Construction of the reciprocal lattice and the Brillouin zones for fcc and bcc lattices
- Calculation of the distances in the Brillouine zone for silicon.

Lattice dynamics

- Force constant matrix and its symmetries
- Dynamic matrix and the equations of motion
- Construction and diagonalization of the dynamic matrix for one fcc monatomic: eigenvalues and displacement patterns
- Diatomic linear chain
- Dispersion curves of real crystals
- Inelastic scattering and measurement of phonon dispersion by neutron scattering

Thermal properties

- From normal modes to phonons as quasi-particles
- Density of vibrational states
- Specific heat in Debye and Einstein models
- Anharmonic potentials and the heat capacity in Dulong Petit regime
- Equation of state of a solid

- Thermal expansion and meaning of the Gruneisen parameter
- Thermal conductivity

Free electrons

- The electron gas at T = 0, steric repulsion
- Density of states in 1, 2 and 3 dimensions
- 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

Electronic bands

- Expansion in plane waves and the central equation
- Bloch waves and new meaning of the moment p
- Construction of the band diagram for the empty lattice
- Opening of the gap at the Brillouin zone borders and its interpretation
- Expansion of the Bloch wave in atomic orbital: tight binding (TB)
- Band energy as a function of TB parameters and neighbors.
- Construction and diagonalization of the tight binding matrix in sp3 basis and first neighbors for silicon
- Interpretation of real bands and their density of states
- Measurement of the dispersion of the bands by electron photoemission resolved in angle

Transport by electrons

- The semiclassic model by packets of Bloch waves, equations of motion
- 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 in the process of scattering
- Microscopic mechanisms that rule the scattering of charges
- The classic model of transport by Drude and its limits
- The electrical conductivity as the integral on the Fermi surface
- Dependence of resistivity from the temperature in a metal
- Heat transport by electrons
- The Wiedemann-Franz law
- Thermoelectric effects (Peltier and Seebeck)

The many-electron problem

- The mean field approach by Hartree
- The Hartree-Fock equations and meaning of the exchange energy contribution
- The interacting gas of free electrons and the density dependent energy
- The Hohenberg and Kohn theorem and the equation of Kohn-Sham
- The density functional method in the local approximation DFT-LDA
- Cellular methods, the muffin tin potential, and the augmented plane waves
- Orthogonalized valence plane waves, the pseudopotential method

Screening by the electron gas

- From Poisson equations to relations between epsilon and susceptibility: classical model
- The Thomas-Fermi model of the electrostatic shield (constant susceptibility)
- The Linhard model of the electrostatic shield (susceptibility depends on q)
- The quantum interpretation of the ineffectiveness of the screen beyond $2k_F$ and the charge density waves
- From the jellium model to the real metal
- Cohesion energy for different structures in simple metals

Magnetic properties

- Definition of magnetization and susceptibility; introduction to the Hamiltonian including vector potential
- Diamagnetism and paramagnetism in solids, why negligible values for susceptibility
- Pauli paramagnetism and Landau diamagnetism for the gas of free electrons
- Electron motion in a magnetic field
- Landau levels and the de Haas - van Alphen effect

Ferromagnetism

- Stoner model for itinerant ferromagnetism in metallic solids
- Effect of temperature in the Stoner model, Curie temperature
- Origin of ferromagnetic interactions in insulating solids and the Heisenberg hamiltonian
- Ferromagnetism in insulators, the Curie temperature and the susceptibility vs T
- Excited magnetic states and the spin waves; other collective excitations in solids
- Ferromagnetic domains

Superconductivity

- Introduction to superconductivity
- Meissner-Ochsenfeld effect: expulsion of the magnetic field
- The thermodynamics of the transition to the superconducting state
- The London and London equations: penetration of currents and magnetic fields
- Origin of the attraction in the Cooper pair, instability of the ground state
- Derivation of the fundamental BCS state
- Existence of the gap, its nature, and definition of the excited states
- Dependence of gap from T, relationship between Tc and gap at T = 0; isotope effect
- The supercorrent as steady state and the critical values of current and magnetic field

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 exercitations. In this academic year 2020/2021, following the indications of the Milano Bicocca university for the Covid 19 emergency, both the lessons and the exercitations will be provided remotely, by uploading the recordings and the related material in asynchronous modality. Still periodic tutoring meeting via Webex in synchronous modality will be organized, so that the students will rise questions and problems related to the Course.

Textbook and teaching resource

PRINCIPAL 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:

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, in order 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, by an oral discussion with written derivations, can also be divided into two steps, at different times: the first one, for the first, simpler part of the course,

Office hours

By appointment writing one e-mail to leo.miglio@unimib.it, or to roberto.bergamaschini@unimib.it. In particular, we warmely suggest to take the remote meeting option, via Webex, at least until the Covid 19 emergency is still in action.