UNIVERSITÀ
DEGLI STUDI DI MILANO-BICOCCA

SYLLABUS DEL CORSO

Solid State Physics

2425-1-FSM01Q001

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 into two parts. In the first part, the three fundamental players of crystalline solids are introduced: the crystal lattice in direct and reciprocal space, lattice vibrations and their thermal effects, free electrons in the approximation of non-interacting particles. Particular attention is given to the techniques for calculating macroscopic quantities on the basis of microscopic variables. The second part includes the charge- and heat-transport phenomena, relative to the electrons moving in the energy bands, as produced by the application of electric, or magnetic fields, and thermal gradients. Also in this part, it is taught that the mathematical modelling is the tool that allows us to link macroscopic effects to the microscopic variables of the system. Towards the end of the course, two hours are devoted to the interactive teaching with the students, one referring to the first part and the other to the second part, in order to answer the collective questions and doubts that emerged from the interaction between the students themselves, which is strongly encouraged.

Contents

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

Part 2
V. Electronic bands in a periodic lattice
VI. Transport of charge by electrons in one electric field
VII. Transport of heat by electrons and thermoelectric effects
VIII. Effects of weak and strong magnetic fields

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 of silicon.

II. Lattice dynamics

- Foundations of lattice dynamics: force constant matrix and its symmetries, dynamical matrix and the equations of motion
- Dispersion relations and displacement patterns of the diatomic linear chain
- Elasticity theory and sound waves
- Construction and diagonalization of the dynamic matrix for one fcc monatomic: eigenvalues and displacement patterns
- Normal modes as collective modes
- Phonons 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 their effects: thermal expansion and the heat capacity of 1-D oscillator
- Thermal expansion and the Gruneisen parameter in 3-D
- Thermal conductivity by lattice vibrations in 3-D

IV. The free-electron gas

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

- The semiclassical 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

VII. Transport of heat by electrons

- Generalization of the Boltzman equation to thermal gradients
- Heat transport by electrons and the Wiedemann-Franz law
- Thermoelectric effects (Peltier and Seebeck) and applications

VIII Effects of magnetic fields

- Effects by weak fields
- Effects by strong fields and Landau energy levels
- Magnetic properties of matter
- The magnetism of free electrons

Prerequisites

Atomic and molecular quantum physics

Elementary introduction to Materials

Elements of calculus for complex variables, special functions, series and Fourier transforms

Teaching form

The course consists of 38 hours of lectures and 12 hours of practice lessons delivery in nature (DE), and 2 hours of discussion with the students, interactive in nature (DI). All teaching hours are scheduled to be in presence, but considering the difficulty of foreign students in obtaining an entry visa in time to participate in the starting lessons, or in the eventuality of particularly intense meteorological events, which could prevent a large part of students to come to the classroom, some lessons/practice lessons, up to a maximum of 30%, could also be delivered in synchronous remote mode, at the same times scheduled for the course.

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

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

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

Semester

Second part of the first semester, so that the advanced course in calculus can provide most of the subjects necessary to follow this course. The students are therefore warmely invited to attend that course with attention and continuity.

Assessment method

The exam consists of a written test with open questions, then discussed during an oral exam of individual correction, which can also focus on other topics covered in lessons or exercises. In particular, the exam consists of a written test with four open questions, including the mathematical derivation of some physical results, or the drawing of some graphs and related commentary.

During the lesson period, however, students who are attending the course will have the possibility of dividing the exam into two partial tests, one relating to the topics of Part 1 of the course and the other relating to the topics of Part 2. Each of these partial exams will consist of a written test with 3 open questions, including the mathematical derivation of some physical results, or the drawing of some graphs and related comments, followed by a short oral discussion on the written result, with some further in-depth analysis, always relating to the topics covered in the lessons. Since this path of partial tests requires students to study in parallel with the lessons, active participation in lessons is strongly recommended. To facilitate the preparation, organize and explain the exam methodology and answer any questions on the topics of the lessons, a meeting will be organized with the interested students before each partial exam, and open to all others. If a student fails the test on the first part, he will have one (only) further opportunity to try it again, before the lessons of the second part of the course are finished; if he fails the test on the second part, he will have one (only) further opportunity to try it again, before the starting date of the second semester.

Office hours

By appointment writing one e-mail to leo.miglio@unimib.it, or to roberto.bergamaschini@unimib.it for questions related to the exams

Sustainable Development Goals

AFFORDABLE AND CLEAN ENERGY | INDUSTRY, INNOVATION AND INFRASTRUCTURE