UNIVERSITÀ
DEGLI STUDI DI MILANO-BICOCCA

# COURSE SYLLABUS

## Solid State Physics

**2324-1-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. 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 peculiar attention in getting the skill of developing analytical models, which allow to solve complicated problems by ingenious simplifications. The second part includes the phenomena related to the electrons in the crystal lattice, returning the band structure and the transport properties, again exploiting the combination of physical reasoning and mathematical analysis. At the end of each subject two hours of exercises will be given, in order to getting familiar with the concepts and improving the comprehesion by a discussion with the students. 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.

### 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
VI. Transport of charge by electrons
VII. Transport of heat by electrons and thermoelectric effects

## 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

## Prerequisites

Atomic and molecular quantum physics

Elementary introduction to Materials

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

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

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

## Semester

First semester at different lesson periodicity. In particular, the lessons will increase in density with the 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 this course with attention and continuity.

## Assessment method

The final examination consists in a written test, discussed and complemented during a following oral exam with individual correction. In particular, the written part is organized in four open questions, including the derivation of some physical results, as followed by an oral discussion/in-depth analysis of what has been written by the student. This modality applies to all the students, independetly on the court they pertain, starting from academic year 2023/2024, who are willing to take in one shot the exam in one of the nine exam sessions, which are organized during the yearly periods that lessons are not taking place. Obiously, the students attending the lessons of the course in one academic year cannot enrol to exam sessions that are taking place before the end of lessons that they are attending.

However, during the teaching time, students attending the course will have the possibility of subdividing the exam into two partials, one concerning the topics of the Part 1 of the course and the other concerning the topics of Part 2. These partial exams consist of a written test with open questions on the topics taught at lesson, including the mathematical derivation of some physical results, followed by a short oral for the discussion about the written test. 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 the others, will be scheduled.
If a student fails the partial test on the first part, she/he will have (only) one other opportunity to try again, within the end of the lessons for the second part of the course; if a student fails the partial test on the second part, she/he will have (only) one other oppurtunity to try again, before the beginning 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