# SOLID-STATE PHYSICS

FIS/03 - 6 CFU - 1° Semester

**Teaching Staff**

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**Office Hours:** Lunedì e Mercoledì 8:00-10:00. È gradito un e-mail di pre-avviso. Possibile anche il ricevimento in altri giorni e orari, da concordare per e-mail.

## LEARNING OBJECTIVES

The course aims at providing the student with the fundamentals of the physics of matter in the solid state, with reference to both experiment and theory. Specific interest will be devoted to the crystal structure, the electronic band structure, the lattice dynamics, and the electronic transport and optical properties of solids. A few lectures will focus on selected advanced topics *(in italics, below)* of current interest in experimental and theoretical solid-state physics.

*Knowledge and understanding.*

Critical understanding of the most advanced developments of Modern Physics, both theoretical and experimental, and their interrelations, also across different subjects.. Adequate knowledge of advanced mathematical and numerical tools, currently used in both basic and applied research. Remarkable acquaintance with the scientific method, understanding of nature, and of the research in Physics. During the course we will present both experimental facts and theoretical models concerning the properties of the solid state of matter, with reference to modern experiments and novel theoretical interpretations.

*Applying knowledge and understanding*

Ability to identify the essential elements in a phenomenon, in terms of orders of magnitude and approximation level, and being able to perform the required approximations. Ability to use analogy as a tool to apply known solutions to new problems (problem solving). In presenting a solid-state physics phenomenon, emphasis will be given to the most important magnitudes, introducing all other magnitudes as successive approximations.

*Making judgements*

Ability to convey own interpretations of physical phenomena, when discussing within a research team.

Developing one's own sense of responsibility, through the choice of optional courses and of the final project. In presenting the different topics, both during the course and during the final exam, links will be given with other courses (mainly, but not only, belonging to the same curriculum), some of which optional, and with possible topics for a research final project, both experimental and theoretical.

*Communication skills*

Ability to discuss about advanced physical concepts, both in Italian and in English.

*Learning skills.*

Ability to acquire adequate tools for the continuous update of one's knowledge. Ability to access to specialized literature both in the specific field of one's expertise, and in closely related fields. Ability to exploit databases and bibliographical and scientific resources to extract information and suggestions to better frame and develop one's study and research activity. Ability to acquire, through individual study, knowledge in new scientific fields. We will often make reference to scientific papers, both reviews and research articles.

## COURSE STRUCTURE

Frontal lectures.

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## DETAILED COURSE CONTENT

**Crystalline solids.** X-ray diffraction. Direct lattices in $d \leq 3$ dimensions. Lattices with basis. Wigner-Seitz cell. Reciprocal lattice. Brillouin zones.

*Real crystals: defects.*

*Other correlated phases of matter. Van Hove correlation function. Amorphous solids, liquids, superlattices, quasicrystals.*

**Free electrons.** Free electron gas. Fermi-Dirac statistics, chemical potential, and other thermodynamic potentials (reminder). Sommerfeld expansion. Electronic specific heat. Effective mass. *Heavy-fermion materials.*

**Electrons in crystalline lattices.** *Kronig-Penney model.* Bloch theorem. Quasimomentum and electronic bands. Special points and `spaghetti' plots. **k·p** Hamiltonian.

***Parameter-dependent Hamiltonians.*** *Hellmann-Feynman and Eppstein theorems. Berry phase and connection. Applications to modern solid-state physics (electrical polarization, AFM: Atomic Force Microscopy, Wannier states and maximally localized states).*

***Electron correlation.*** *Hartree-Fock approximation. From Thomas-Fermi approximation to the Hohenberg-Kohn theorem. Density Functional Theory (DFT).*

***Stability of matter.***

**Quasi-free electrons.** Fermi surfaces of metals. Density of states. Electronic topological transitions (van Hove singularities). Band gaps. Metals, semiconductors, insulators. Tight-binding method (LCAO). *Other* *numerical methods (OPW, APW, KKR).* Effective mass again. 2D examples: square lattice, graphene.

**Mechanical properties of solids.** Cohesion energy. Elastic properties of solids. Lattice dynamics. Phonons in solids. Einstein and Debye models: lattice specific heat. *Anharmonic effects.*

**Transport properties of solids.** Bloch electrons. Electrical conductivity and heat conduction of metals. *Wiedemann-Franz law.* Drude and Sommerfeld models. Hall effect. *de Haas-van Alphen effect. Quantum Hall effect.*

***Optical properties of solids.*** *Plasmons.*

***Electronic phases with broken symmetries.***

- *Ferromagnetism. Stoner model. Mean-field approximation. Spin waves.*
- *Antiferromagnetism. Slater model. Spin density waves.*
- *Peierls instability. Charge density waves. Solitons.*
- *Pairing instability: superconductivity. Phenomenology. Ginzburg-Landau theory. Electron-phonon coupling. BCS theory. Josephson effect. Superconducting fluctuations. High-$T_c$ and other `exotic' superconductors: cuprates, $MgB_2$, pnictides, ...*

***Topological insulators.***

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## TEXTBOOK INFORMATION

G. Grosso, G. Pastori Parravicini, *Solid state physics* (Oxford, Academic Press, 2014 : 2nd ed.)

Fuxiang Han, *A modern course in the quantum theory of solids* (Singapore, World Scientific, 2013)

J. Sólyom, *Fundamentals of the physics of solids* (Heidelberg, Springer, 2010) : 3 vols.

N. W. Ashcroft, N. D. Mermin, *Solid state physics* (Saunders, Philadelphia, 1976)

J. M. Ziman, *Principles of the theory of solids* (Cambridge University Press, Cambridge, 1965)

C. Kittel, *Quantum theory of solids* (New York, J. Wiley & Sons, 1963)

W. Jones, N. H. March, *Theoretical solid state physics* (New York, Dover, 1985) : 2 vols.

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