UNIVERSITÀ
DEGLI STUDI DI MILANO-BICOCCA

COURSE SYLLABUS

Physics of Materials With Laboratory

2627-3-ESM01Q017

Aims

Provide the student with the knowledge base for understanding the physical properties of materials and their measurement.

The main training objectives are:

- knowledge and ability to understand the physical properties of materials;
- knowledge and ability to understand the physical properties of materials applied to the main uses;
- autonomy of judgment in the analysis of physical properties and in the setting up of scientific experiments;
- communication skills in the presentation of complex physical theories and in the reporting of scientific experiments;
- ability to learn independently from additional teaching material, manuals and technical specifications of the instrumentation.

Contents

- Material properties (mechanical, vibrational, thermal, electronic, magnetic, dielectric, optical,..)
- Materials (metals, semiconductors, dielectrics, magnets, piezoelectrics,...)
- Solid state devices (photovoltaic cell, LED, thermocouple, transistor, ...).
- Instrumentation of a materials physics laboratory (electrical measurements, optical measurements, ...)

Detailed program

LABORATORY OF PHYSICS OF MATERIALS

The laboratory consists of a series of experiences with a duration of two or three afternoons each, focusing mainly on the properties of semiconductor materials. The purpose of the experiences is mostly to develop a critical sense and autonomy in the process of measuring the physical properties of the materials. Experiences include:

- the Hall measurement of electrical and doping properties of semiconductors;
- voltage-current characteristics of a p-n junction;
- measurement of absorption and reflection properties;
- measurement of the efficiency of photovoltaic cells as a function of the wavelength of the incident light;
- life time measurements of photo-excited carriers.

INTRODUCTION TO THE LABORATORY

Photons, spectroscopy, transmission, absorption, emission, interference, light sources, lenses and mirrors, dispersive elements, monochromator, detectors, spectrophotometer, spectroscopic measurement parameters, safety, semiconductors, electrons and holes, dopants, pn junction, diode, photodiode, photovoltaic cell, LED, conductivity, mobility, ohmic contacts, Hall method, Van der Pauw method, optical absorption in semiconductors.

THEORY - PART ONE

Crystals and bondings. Crystalline, polycrystalline and amorphous solids; crystal structures; bonding in solids: ionic, covalent, metallic, hydrogen, and van der Waals bonds; Madelung constant; Bravais lattices; unit cell and Wigner–Seitz cell; conventional cell; close-packed structures; Miller indices; plane waves and lattices; Fourier series for the description of periodic properties of materials; direct and reciprocal lattices.
Mechanical properties. Uniaxial, shear and hydrostatic stress; stress–strain curves; elasticity; plastic deformation; brittle and ductile materials; yielding; strain hardening; necking; fracture; resilience and toughness; Young’s modulus; shear modulus; bulk modulus; Poisson’s ratio: meaning and limits; interatomic potential and Young’s modulus; correlation between bond type and Young’s modulus; point and extended defects; dislocations and Burgers vector; iron and steel; strain tensor; stress tensor; example: epitaxial germanium on silicon.
Vibrational and thermal properties. Dulong–Petit heat capacity derived from the equipartition theorem; independent oscillators; monoatomic linear chain; dispersion relation ?–?; phase and group velocity; speed of sound; standing waves; Brillouin zone; meaning of the periodicity of ?(?) in the reciprocal lattice; introduction to the diatomic linear chain; acoustic and optical branches; dispersion in crystals with multiple atoms per unit cell; interaction between optical branches and electromagnetic radiation (why it is called the optical branch); finite-size effects in crystals; quantization of vibrations and phonons; review of Bose–Einstein statistics; Einstein model; limitations of the Einstein model and results of the Debye model; dispersion relations in 3D solids; reciprocal lattice of the FCC structure and examples of dispersion in aluminum, diamond and silicon; order-of-magnitude estimate of diamond vibrational frequencies from Young’s modulus; thermal expansion; phase transitions; melting; Lindemann criterion; definition of thermal conductivity; microscopic model of thermal conductivity.
Classical properties of metals. Drude model of conductors; equation of motion of an electron in a static electric field; scattering time; minimum scattering time; thermal and drift velocities; mobility; conductivity; Hall effect; electric displacement D; polarization P; D–E–P relationship; dielectric function; electric susceptibility; meaning of the real and imaginary parts of ?; refractive index and dielectric function; extinction coefficient; absorption coefficient; evanescent waves; equation of motion of an electron in a time-varying electric field; plasma frequency; total reflection in metals; derivation of reflection using complex numbers; estimate of penetration depth in aluminum; electronic thermal conductivity; Wiedemann–Franz law; Lorenz number; introduction to the thermoelectric effect; Seebeck coefficient; thermocouple; thermoelectric generator; Peltier effect; limitations of the Drude model.

THEORY - PART 2

Quantum properties of electrons in solids. Assumptions of the Sommerfeld model; semiconductors and metals; free electrons in a box; Born–von Karman periodic boundary conditions; minimum k; electron wave momentum; Fermi energy and Fermi wavevector; Fermi energy of free electrons in a box; density of states; review of Fermi–Dirac statistics; electronic heat capacity; Bloch theorem; meaning of k with respect to wavefunction symmetry; classification of free electrons according to Bloch; momentum and crystal momentum; weakly bound electrons (results only); phase and group velocity of electrons; equation of motion of an electron in a crystal; effective mass; transport at T = 0 in semiconductors and metals; transport in real metals; holes; energy bands in 3D solids; band structures of Al, Si, Ge and GaAs; density of states in 3D solids.
Semiconductors.

Formulation of semiconductor statistics; approximate position of the chemical potential; approximation of the Fermi function; carrier density and temperature; effective density of states; intrinsic carrier concentration; position of the chemical potential; hydrogenic model for extrinsic impurities: orbital energy and radius; qualitative and quantitative statistics of extrinsic semiconductors; chemical potential position; mass action law; conductivity in semiconductors.
Semiconductor devices. Introduction to the pn junction; junction electrostatics; electric field and potential; depletion-region width; band bending; chemical-potential equilibration; dynamic equilibrium of majority and minority carrier currents; effect of external bias; diode equation; illuminated junction; photodiode; photovoltaic cell; efficiency and limits; light-emitting diode (LED); junction field-effect transistor (JFET); metal–oxide–semiconductor (MOS) system; MOSFET transistor; memory cell; cell arrays; semiconductor technology.
Magnetic materials. Magnetic dipole; magnetic energy of a dipole; dipoles in materials; magnetization; classification of magnetic phenomena; ferro-, antiferro-, ferri-, para-, and diamagnetism; external and internal magnetic fields; magnetic field and magnetic induction; magnetic susceptibility; relative magnetic permeability; energy of para- and diamagnetic solids; review of magnetism in the hydrogen atom; gyromagnetic ratio / Landé g-factor; multi-electron atoms; Curie paramagnetism in a two-level system; Pauli paramagnetism; spontaneous magnetic ordering: ferro-, antiferro-, and ferrimagnetism; microscopic origin and exchange energy; hyperbolic tangent; Heisenberg Hamiltonian and two-level ferromagnetic system; magnetic energy and Curie temperature; spontaneous magnetization versus temperature; paramagnetism above the Curie temperature: Curie–Weiss law; Weiss domains; Bloch walls; hysteresis loop M vs B? and B vs H; power dissipation in the hysteresis cycle; soft and hard magnets.
Dielectrics. Dielectric permittivity and susceptibility; electric displacement; polarization; polarizability; atomic, ionic and orientational polarizability; mean and local fields in materials; Clausius–Mossotti relation; dielectric issues in transistors; frequency response of dielectrics: qualitative explanation; Lorentz model without dissipation; complete Lorentz model; imaginary dielectric constant and Joule dissipation; dielectric function for two resonances (ionic and atomic); dielectric function for N resonances; relationship between the Lorentz model and absorption in solid-state bands; TART model (transmission–absorption–reflection–transmission); relationship between energy gap and static dielectric constant; impurities in dielectrics and color; ferroelectrics; piezoelectrics; electrical breakdown.
Superconductors. Qualitative introduction to superconductors; zero resistance; critical temperature, critical magnetic field, and critical current; Meissner effect; applications.

Prerequisites

Good knowledge of General Physics and techniques of integral and differential calculus. Basic knowledge of Quantum Physics.

Teaching form

34 lessons of 2 hours and 1 lesson of 1 hour held in classroom for the Materials Physics module and the introduction to the lab;
9 experimental activities of 4 hours each held in the laboratory;
Lectures and workshops are held in Italian.

Textbook and teaching resource

- Solid State Physics: An Introduction, di Philip Hofmann (Main reference book)
- Notes from the lecturer.

Semester

Second Semester

Assessment method

In summary the tests consist of:

- Interviews on the topics covered in class;
- Interview on the laboratory report;
- Interview on laboratory experiences.
- The details of the tests are described below.
- The Physics examination of the Materials with the Laboratory is divided into oral tests, with the compilation of a laboratory report. The Materials Physics course with Laboratory is composed of 10 CFU. The exam is divided into modules, one relative to the laboratory and two modules dedicated to theory. These three modules can be passed either simultaneously or separately.

The laboratory module includes the evaluation of a report on one of the practical experiences of the laboratory. The mark on the report is based on the correctness, completeness and clarity of the exposure of the measurements. The oral test instead analyzes the knowledge of all the demonstrations that the student carried out in the laboratory. For this module it is not necessary to have a thorough knowledge of the theory, which is instead the object of the other modules, but it is sufficient to know the minimum notions of physics of the materials necessary for understanding the experiment. These minimum notions are those reported in the laboratory sheets related to the experiences carried out. Obviously, it is assumed that the arguments of the laboratories of previous years are known. This module mainly analyzes the understanding of the experiment methodology, the understanding of the instrumentation (for example the operation, instrumental limits, procedures), and the analysis of data (uncertainties, processing, presentation).

The two modules of Physics of Materials are instead focused on the theory of physics of materials. The details of the subdivision of the two modules are reported in the e-learning section. For these modules, the understanding of physical phenomena, the ability to reduce complex phenomena to simple models, the ability to use mathematical models to quantify the physical properties of materials will be evaluated.

The Laboratory module and the first Materials Physics module are delivered first and therefore can be taken even before the end of the course (ongoing evaluation).

Office hours

At the end of the lectures or by appointment.

Sustainable Development Goals

QUALITY EDUCATION | AFFORDABLE AND CLEAN ENERGY | DECENT WORK AND ECONOMIC GROWTH | INDUSTRY, INNOVATION AND INFRASTRUCTURE | RESPONSIBLE CONSUMPTION AND PRODUCTION |

CLIMATE ACTION