Academic Year 2019/2020

Class: 84200 Physics of Semiconductor Devices and Memories M — Credits: 6 — Hours: 60 — Semester: 1st

First module of the integrated course **87193 - Physics of Semiconductor Devices, Memories and Sensors M C.I.** The second module is **84418 - Advanced Solid-State Sensors M (Prof. S. Reggiani) — Credits: 6 — Hours: 60 — Semester 2nd**

Programme: 0934-Electronics and communication science and technology

Teacher: Massimo Rudan

Note: the audio recordings of the lessons delivered in the Academic Year 2019-2020 are posted in the Teacher's website.

Physics of Semiconductor Devices and Memories M 2019-2020

Learning outcomes

Knowledge about the fundamentals of quantum mechanics and band theory of solids; knowledge about the physical phenomena underlying the transport of charged carriers in solids. Competencies: (general) to have critical understanding of technical and scientific tools; communication skills; to be able to work in an international context; (specific) to understand the methods for investigating advanced solid-state devices; to determine the important microscopic and macroscopic parameters involved in the functioning of semiconductor devices; to perform numerical analyses of semiconductor devices. Detailed contents: introductory part where the basic relations of quantum mechanics are shown; theory of bands in crystals; description of the different hierarchical approached to the transport theory; lattice vibrations; treatment of the main scattering mechanisms in semiconductors; absorption of light in semiconductors. Basic semiconductor devices: *p-n* junction; Shockley theory; current-voltage relation of the *p-n* junction; width of the space-charge region and barrier capacitance. MOS capacitor. Relations between semiconductor charge and surface potential in the different operating regions. Operating regimes. Structure of the MOS transistor. Calculation of the drain current. Expression of the current. Gradual channel approximation. Calculation of the current-voltage relation. Linear-parabolic model of the MOS transistor.

Prerequisites

Basic concepts of mathematics and physics acquired from earlier courses.

Basic concepts about the electron devices.

In this course, further mathematical and physical concepts, not necessarily elementary, will be used. They will be explained as necessary during the lessons. The use of such concepts cannot be disposed with, they actually constitute the cultural basis of the course itself.

Course contents

Presentation and aims of the course. Schedule. Notions that should already be known to the Students. Exams. Contents. References.

Variational calculus. Hamilton's principle. Maupertuis principle. Fundamentals of electromagnetism. Analogy between the variational principles of Optics and Mechanics. Hypothesis of generalization of Mechanics.

Maxwell equations. Calculation of the energy of the electromagnetic field *in vacuo* in terms of linear harmonic oscillators.

Planetary model of atoms and explanation of some atomic phenomena by means of such a model.

Experimental results not explained by the "classical" laws. Stability of atoms, spectral lines of excited atoms, photoelectric effect.

Black-body radiation. Planck's hypothesis, Planck's law. Einstein's theory of the photoelectric effect. Compton effect and its explanation using the hypothesis of the photon.

Hall effect. Davisson and Germer's experiment. Bohr's hypothesis. Quantization of the dynamical quantities.

De Broglie's hypothesis. Wave function for the motion in free space. Perturbation induced by a measurement. Normalization of the wave function. Schrödinger equation independent of time.

Hamiltonian operator: definition and properties. Examples: free particle, particle confined within a one-dimensional box with infinite walls.

Scalar product of functions. Hermitian operators. Properties of the eigenvalues and eigenfunctions of Hermitian operators. Completeness of a set of functions.

Superposition of states. Deduction of the Schrödinger equation dependent on time. Norm conservation. Wave packet.

Introduction to the general methods of Quantum Mechanics. Successive measurements of position and momentum. Measurements of energy. Theorems about operators. Simultaneously observable quantities. Commutative operators. Examples.

Statistical concepts associated to quantum operators. Expectation value of an operator. Demonstration of the uncertainty principle. Minimum-uncertainty wave function. Time derivative of the expectation value. Ehrenfest theorem.

Examples of solution of the Schrödinger equation. Potential-energy step. Wave packet and limiting cases. Potential-energy barrier. Tunnel effect. Potential-energy well.

Introduction to the problem of the linear harmonic oscillator. Importance of the problem. Calculation of the eigenvalues and eigenfunctions.

Quantization of the energy and momentum of the electromagnetic field. Concept of photon.

Symmetrical or anti-symmetrical functions and operators. Systems made of identical particles. Fermions and bosons. Pauli exclusion principle. Statistical treatment of sets of identical particles.

General concepts about the equilibrium statistics. Derivation of the Fermi-Dirac statistics. Classical limit of the F-D statistics. Stirling approximation for the factorial.

Derivation of the Bose-Einstein statistics. Calculation of the density of states for the electromagnetic field within a box. Derivation of the Planck law. Calculation of the Lagrange multiplier within the Planck law.

Lattice vibrations. Second-order expansion of the potential energy. Diagonalization of the elastic-coefficient matrix. Classical treatment of the small oscillations.

Separation of the Hamiltonian of the electrons from that of the nuclei. Adiabatic approximation. Single-electron Hamiltonian.

Introduction to crystals. Direct lattice. Characteristic vectors. Translational vectors. Wigner-Seitz cell. Description of the crystal structure of silicon and III-V compounds.

Translational operators. Periodic operators. Bloch theorem and Bloch functions. Periodicity of the eigenvalues of the translational operators.

Krönig-Penney model. Hint about the calculation of the dispersion relation in three dimensions. Symmetry of the eigenvalues. Energy bands. Example: silicon. Density of states in the phase space.

Wave packets in a periodic potential. Definition of the effective-mass tensor.

Density of states in energy for a parabolic band. Form of the dispersion relation of the conduction and valence bands for Ge, Si, and GaAs.

Distribution function. Density of states in the general case. Definition of hole concentration. Qualitative discussion about conductors, insulators, and semiconductors at equilibrium.

Calculation of the intrinsic concentration. Fermi integrals and exponential approximation for them. Examples of the parameters determining the gap and intrinsic concentration in Ge, Si, and GaAs.

Dynamics of an electron in a crystal. Definition of the average velocity of electrons and holes. Comments. Equivalent Hamiltonian. Effective-mass theorem.

Effect of the dopants. Calculation of the extrinsic concentrations in the uniform case. The case of non-degeneracy and complete ionization. Compensation effect.

Examples of band diagrams for silicon. The non-uniform case. The Poisson equation.

Liouville theorem. Boltzmann transport equation (BTE). Relaxation time.

Moments' method. Moment of order zero of the BTE. Physical meaning of the terms appearing in the moment of order zero.

Moment of order one of the BTE. Steady-state approximation. Mathematical model of semiconductor devices.

Heuristic derivation of the transport equation. Mobility and conductivity. Quasi-Fermi potentials. Boundary conditions of the model of semiconductor devices.

Thermal recombination-generation term. Optical generation. Concept of laser. Concluding remarks about optical transitions. Absorption of radiation in a semiconductor.

Macroscopic mobility models. Matthiessen rule. Dependence of mobility on phonon collisions, concentration of ionized impurities, and field component normal to an interface. Examples of numerical simulation of mobilities, and comparison with experiments.

p-n junction. Built-in potential. Solution of the Poisson equation at equilibrium. Space-charge and quasi-neutral regions.

Non-equilibrium condition. Forward and reverse bias. Qualitative description of the junction's functioning. Shockley theory. Current-voltage relation of the *p-n* junction. Dependence on temperature.

Full depletion of the space-charge region in reverse bias. Form of the charge density, electric field, and electric potential. Width of the space-charge region and barrier capacitance. Meaning of the diffusion length.

MOS capacitor. Relations between semiconductor charge and surface potential in the different operating regions. Solution of the Poisson equation in the MOS capacitor with a constant dopant concentration.

Operating regimes (flat band, accumulation, etc.). Approximate relations between charge per unit area and surface potential.

Structure of the MOS transistor (n channel). Calculation of the drain current. Expression of the current in integral form.

Gradual-channel approximation. Calculation of the current-voltage relation of the MOS transistor. Linear-parabolic model.