Academic Year 2016/2017

Class: 78733 Solid-State Electronics — Credits: 6 — Hours: 60 — Semester: 2nd

Programme: 0934-Electronics and communication science and technology
Programme: 8896-Sustainable technologies and biotechnologies for energy and materials

Teacher: Massimo Rudan

Note: the audio recordings of the lessons delivered in the Academic Year 2016-2017 are posted in the Teacher's website.

Solid-State Electronics 2016-2017

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; to be able to select and apply numerical TCAD 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; derivation of the macroscopic elastic properties of solids. Case studies of solid-state device modeling using advanced professional software tools.

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.

Analogy between the variational principles of Optics and Mechanics. Hypothesis of generalization of Mechanics. 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. Contraction of the wave function. 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.

Symmetric or anti-symmetric functions and operators. Systems made of identical particles. Fermions and bosons. Constructing symmetrical or anti-symmetrical wave functions basing upon the solution of the Schrödinger equation. 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. Derivation of the Bose-Einstein statistics.

Calculation of the density of states for the e.m. field within a box. Derivation of the Planck law. Calculation of the Lagrange multiplier within the Planck law.

Time-dependent perturbation theory. Reduction to a set of differential equations in the coefficients of the expansion, transformation into an integral equation. Solution of the equations. Fermi's golden rule and its properties.

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

Adiabatic approximation. Single-electron Hamiltonian.

Introduction to crystals. Direct lattice. Characteristic vectors. Translational vectors. Wigner-Seitz cell. 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. Definition of the effective-mass tensor.

Wave packets in a periodic potential. Symmetry of the eigenvalues. Energy bands.

Example: silicon. Density of states in the phase space. 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 the 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.

Definition of the average velocity of electrons and holes. Comments.

Dynamics of an electron in a crystal. 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. Examples of band diagrams for silicon. Compensation effect.

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 1 of the BTE. Simplifications and meaning of the terms appearing in the moment of order 1 of the BTE. Electron-temperature tensor. Electron-temperature tensor in the equilibrium case. Relaxation-time tensor.

Moment of order 1 for a single valley. Current density for a single valley. Simplifications for the case of a low magnetic field. The simplified diffusive term. Mobility and diffusivity tensors. Compensation of anisotropy when the perturbation with respect to equilibrium is small.

Drift-diffusion transport equations including the magnetic field. Einstein relations. Mathematical model of semiconductor devices. Quasi-static approximation. Order of magnitude of mobility and diffusivity.

Dependence of mobility on temperature and doping concentration.

Purely Ohmic equations including the magnetic field. Use of the Ohmic equations in the measurement technique based on the Hall effect. Hall voltage and Hall coefficient.

Application of the Fermi Golden Rule to the constant perturbation and to the harmonic perturbation. The case of the screened Coulomb potential. Thermal generation-recombination. Explanation of the atoms' stability.

The class has been supplemented with seminars on advanced research activities related to semiconductor modeling and simulation.

In the years 2013-2014 and 2014-2015 the part of the class devoted to TCAD has been carried out in the Laboratory and dealt with:
Introduction to TCAD. TCAD practice on typical semiconductor devices.