Физика двумерных систем

Лекторы:
Василий Кравцов

Ассистент:
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Язык:
English

Трудоемкость:
6 з.е.

Форма контроля:
Экзамен

Образовательная программа:

Нанофотоника
1, 3 семестры

Гибридные материалы
1, 3 семестры

Квантовые материалы
1, 3 семестры

Компьютерное моделирование квантовых и нанофотонных систем
1, 3 семестры

Лекции (ак.час)*	**Практические занятия (ак.час)**	**Лабораторные занятия (ак.час)**
28		
***1 академический час = 45 минутам**		

В рамках данного курса студенты познакомятся с основой электронной теории полупроводников, основными полупроводниковыми приборами.

Содержание курса

Plan of a course

Структура курса

Part I. Foundations of semiconductor electronics (autumn)

Fundamentals of the electronic theory of semiconductor:

1. **Band structure and statistics of charge carriers in semiconductors (1 lecture):** Band structure of semiconductors, electrons and holes. Effective mass and its origin. Direct-gap and indirect-gap semiconductors - examples of silicon, germanium and gallium arsenide. Carrier statistics and calculation of the Fermi level. Doped semiconductors, estimate of donor level energy. Carrier concentration in doped semiconductor vs temperature. Heavily doped semiconductors.

2. **Low-dimensional systems (1 lecture):** The concept of heterostructure. Dimensional quantization and quantum wells. Two-dimensional semiconductors based on mono- and bi-layers: graphene, bilayer graphene, transition metal chalcogenides. Band structure of basic two-dimensional materials. Application of the tight binding method for calculations of the band structure.

3. **Kinetic theory of transport in semiconductors: general concepts (2 lectures):** Boltzmann kinetic equation for the single-particle distribution function. Collisions of carriers with impurities, phonons, and with each other. Quantum mechanical calculation of the scattering probability. The collision integral in the kinetic equation for various scattering mechanisms.

4. **Electrical conductivity of semiconductors (1 lecture):** Transport relaxation time and its microscopic calculation for scattering by impurities and phonons. Calculation of conductivity in uniform fields and its dependence on temperature for semiconductors and metals. Electrical conductivity of graphene. Diffusion of charge carriers and electrochemical potential. Relation between mobility and diffusion coefficient.

5. **Thermo- and galvano-magnetic phenomena (1 lecture):** Kinetic equation in the presence of a temperature gradient. Calculation of electronic thermal conductivity and Seebeck coefficient (example of electrons in graphene). Operating principle of a thermoelectric generator and a Peltier element. Kinetic equation in a magnetic field. Hall effect and calculation of Hall resistance. Features of the Hall effect in a two-dimensional system. A method for measuring the carrier mobility using the Hall effect.

6. **(*) "Advanced" methods for solving the kinetic equation (1 lecture):** Variational principle for the distribution function. Calculation of the graphene conductivity limited by electron-hole scattering using the variational principle. Hydrodynamic approach to kinetic equation. Analysis of electrical and thermal conductivity near the neutrality point in graphene.

7. **Recombination of charge carriers in semiconductors (1 lecture):** Origins of nonequilibrium electrons and holes: photoexcitation and electrical injection of carriers. The concept of quasi-Fermi levels. Microscopic mechanisms of recombination of electrons and holes: radiative recombination, Auger process, recombination with phonon emission. Calculation of the rate and characteristic time of radiative recombination.

Basic semiconductor devices.

8. **Contact phenomena in semiconductors (1 lecture):** P-n-junction and its band diagram. Calculation of the field distribution in the p-n-junction (Poisson's equation). Depletion layer width. Metal-semiconductor contact (Schottky contact), calculation of its band diagram. Features of screening in two-dimensional systems, features of two-dimensional p-n-junctions and Schottky contacts, methods of their calculation.

9. **Current-voltage characteristic of the p-n junction (1 lecture):** Macroscopic equations of drift and diffusion for electrons and holes, their simplification for the doped and depleted regions. Shockley theory for the recombination-limited current. Behavior of p-n junction under reverse bias. Applicability limits of the drift-diffusion theory for ultrashort p-n-junctions. Application of p-n-junctions for rectification (detection) of radiation.

10. **Current-voltage characteristic of "metal-semiconductor" structure (1 lecture):** Drift-diffusion theory for the transport of majority carriers. Microscopic boundary conditions at the contact with the metal (surface recombination). Current limitation by carrier injection and diffusion in a semiconductor. Applications of Schottky contacts.

11. **Metal-oxide semiconductor field-effect transistors (MOSFETs) (2 lectures):** Electrostatics of MOS - structures, dependence of the carrier concentration on the gate voltage. Inversion layer. The principle of field-effect transistor operation. Drift-diffusion model of carrier transport in a field-effect transistor. Nonlinear section of current-voltage characteristic and current saturation mechanisms: velocity saturation and channel cutoff. Characteristics of a graphene-based field effect transistor.

12. **Miniaturization of MOS transistors and scaling laws (1 lecture):** The cutoff frequency of the field-effect transistors as a logic switch mode and as a signal amplifier. External and internal factors affecting the cutoff frequency. Dependence of the cutoff frequency on the channel length for drift-diffusion and ballistic transport modes. Scaling laws for frequency and power dissipation. The problem of threshold voltage reduction. Effects of doping density fluctuations and structural parameters in nanoscale field-effect transistors.

Рекомендуемые ресурсы

Books

1. S.M. Sze, Y. Li, K.K. Ng. “Physics of semiconductor devices” John Wiley & Sons (2021)

2. N. W. Ashcroft, N. D. Mermin, Solid state physics. London: Holt, Rinehart and Winston, (1976)

3. T. Ando, A B. Fowler, F. Stern. "Electronic properties of two-dimensional systems." Reviews of Modern Physics vol. 54 iss. 2 p. 437 (1982)

4. Enoki T., Ando T. (eds.). “Physics and chemistry of graphene: graphene to nanographene” Pan Stanford Publishing (2013)

5. S. Datta “Quantum transport: atom to transistor” Cambridge University Press (2005)

Papers

6. L. Venema “Silicon electronics and beyond” Nature 479 p. 309 (2011) – collection of papers devoted to alternative principles of field-effect transistors

7. H. Lu, A. Seabaugh. "Tunnel field-effect transistors: State-of-the-art" IEEE Journal of the Electron Devices Society vol. 2 iss. 4 p. 44-49 (2014); S. Cristoloveanu, J. Wan, A. Zaslavsky “A review of sharp-switching devices for ultra-low power applications” IEEE Journal of the Electron Devices Society,vol. 4 iss. 5, 215-226 (2016)

8. S. Salahuddin, S. Datta “Use of negative capacitance to provide voltage amplification for low power nanoscale devices” Nano letters,vol. 8 iss. 2, 405-410 (2008); W. Cao and K. Banerjee “Is negative capacitance FET a steep-slope logic switch?” Nat. Commun. vol. 11, p. 196 (2020)

9. F. Schwierz “Graphene transistors: status, prospects, and problems” Proceedings of the IEEE vol. 101 iss. 7, p. 1567-1584 (2013)

10. M. Asada, S. Suzuki, and N. Kishimoto “Resonant tunneling diodes for sub-terahertz and terahertz oscillators” Jpn. J. Appl. Phys. vol. 47, p. 4375 (2008)

11. F. Koppens, T. Mueller, P. Avouris, A. Ferrari, M. Vitiello, M. Polini. “Photodetectors based on graphene, other two-dimensional materials and hybrid systems” Nature nanotechnology,vol. 9 iss. 10, 780-793 (2014); A. Rogalski, M. Kopytko, P. Martyniuk “Two-dimensional infrared and terahertz detectors: Outlook and status” Applied Physics Reviews,vol. 6 iss. 2, 021316 (2019)

12. M. S. Vitiello, G. Scalari, B. Williams, P. De Natale “Quantum cascade lasers: 20 years of challenges” Optics express vol. 23 iss. 4, p. 5167-5182 (2015)

Политика оценивания

Баллы начисляются за домашние задания и экзамен