EE 418/518 Quantum Mechanics for Engineers

Time and place: T, R TBD

The course has two components: lectures and labs

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Office Hours: Tuesday and Thursday 2:00 pm-3:00 pm and 5:00 pm-6:00pm
312C and 312B Bonner Hall, Department of Electrical Engineering

Objectives:
ABC of all nanosciences and nanotechnologies is quantum mechanics. The overwhelming majority of quantum mechanics courses are taught in a traditional way beginning with the history of the development of quantum mechanics, basic concepts, comparisons between classical and quantum mechanics, theory of operators, and only after that the simplest applications of quantum-mechanical principles are considered. This approach is successful in physics departments where students specialize in science and education but it's inappropriate in schools of engineering and applied sciences with engineering design oriented programs in nanoelectronics. Here we use a different way of teaching quantum mechanics. Students will acquire and learn quantum-mechanical notions (a) considering numerous examples of real nanostructures, (b) using Java applets, and (c) carrying out lab experiments devoted to main concepts of quantum mechanics. First, students study the fundamentals of quantum mechanics such as wave-particle duality, wave function, quantum states, and quantization. Then apply the quantum-mechanical theory to analysis and design of an artificial atom – a quantum dot (smallest nanostructure), and draw an analogy between the quantum dot and the smallest real atom of hydrogen. Next, we consider more complex nanostructures such as quantum wires, quantum wells, and double-quantum-well diode. In the concluding lectures, a short introduction to technology of nanoscale materials and devices will be presented.

The main goals of the EE418/518 course are to teach students the basics of nanostructures, prepare the solid ground for taking courses in nanoelectronics, nanophotonics, and NEMS technology that are offered at UB, and educate engineers for the rapidly growing nanoelectronics and nanotechnologies market.

Grading: Post-test: 10 %, Homework: 20%, Two Exams: 30 %, Lab: 30 %, Small Design Project: 10 %, Extra credit: 2% - Pre-test.

Straight scale will be used for grading with:

(85< - 100)% - A ; (80 - <85)% - A- ; (75 - <80)% - B+ ; (70 - <75)% - B ; (65 - <70)% - B- ;

(60 - <65)% - C+ ; (55 - <60)% - C ; (50 - <55)% - C- ; (45 - <50)% - D+ ; (40 - <45)% - D ;

<41% - F.

Textbook: Vladimir V. Mitin**,** Dmitri I. Sementsov**,** Nizami Z. Vagidov, **Quantum Mechanics for Nanostructures**, Cambridge University Press, 2010, 431 p, ISBN 978-0-521-76366-0.

Recommended reading: Vladimir V. Mitin**,** Viatcheslav A. Kochelap**,** Michael A. Stroscio, **Introduction to Nanoelectronics: Science, Nanotechnology, Engineering, and Applications**, Cambridge University Press, 2008. In the book, you will find how quantum mechanics works in cutting edge nanoelectronics and nanotechnology.

Pre-requisites: Senior standing for undergraduates (EE 418) or graduate standing for EE 518.

LECTURES

Topics:

1. Introduction: Nanoworld and quantum physics (Chapter 1)
2. Short review of classical motion of particles (Appendix A)
   2.1 Newton's second law of motion
   2.2 Work and potential energy
   2.3 Kinetic and total mechanical energy
   2.4 Equilibrium conditions for a particle
   2.5 Oscillatory motion of a particle
3. Short review of electromagnetic fields and waves (Appendix B)
   3.1 Equations of electromagnetic field
   3.2 Electromagnetic waves
   3.3 Reflection of plane wave from the interface between two media
   3.4 Light and its wave properties
4. Wave-particle duality and its manifestation in radiation and particle's behavior (Chapter 2)
   4.1 Blackbody radiation and photon gas
   4.2 Quantum character of interaction of radiation with matter
   4.3 Wave properties of particles
   4.4 The uncertainty relations
   4.5 World of nanoscale and wave function
   4.6 The Schrödinger equation
5. Layered nanostructures as the simplest systems to study electron behavior in one-dimensional potential
   5.1 Motion of a free electron in vacuum
   5.2 Electron in a potential well with infinite barriers
   5.3 Electron in a potential well with finite barriers
   5.4 Propagation of an electron above the potential well
   5.5 Tunneling: propagation of electron in the region of a potential barrier
6. Additional examples of quantized motion (Chapter 4)
   6.1 Electron in rectangular potential well (quantum box)
   6.2 Electron in a spherically-symmetric potential well
   6.3 Quantum harmonic oscillator
   6.4 Phonons
7. Approximate methods of finding quantum states (Chapter 5)
   7.1 Stationary perturbation theory for a system with non-degenerate states
   7.2 Stationary perturbation theory for a system with degenerate states
   7.3 Non-stationary perturbation theory
   7.4 Quasiclassical approximation
8. Quantum states in atoms and molecules (Chapter 6)
   8.1 Hydrogen atom
   8.2 Emission spectrum of the hydrogen atom
   8.3 Spin of an electron
   8.4 Many-electron atoms
   8.5 Wave function of a system of identical particles
   8.6 Hydrogen molecule
9. Quantization in nanostructures (Chapter 7)
   9.1 Number and density of quantum states
   9.2 Dimensional quantization and low-dimensional structures
   9.3 Quantum states of an electron in low-dimensional structures
   9.4 Number of states and density of states for nanostructures

9.5 Double quantum-dot structure (artificial molecule)
9.6 Electron in a periodic one-dimensional potential
9.7 One-dimensional superlattice of quantum dots
9.8 Three-dimensional superlattice of quantum dots

10. Short introduction to nanostructures fabrication
11. Short introduction to devices with new functionalities based on nanostructures.

LABS

Nanoscience and Nanotechnology Laboratory, 312B Bonner Hall

LAB MANUAL: The students are required to purchase the **"EE418/518 Quantum Mechanics for Engineers Lab Manual"** from the University bookstore located at the UB Commons (North Campus). The handouts for all the experiments are contained in the Lab manual.

GRADING: 30 % of the final EE 418/518 grade is determined from your lab reports. A grading curve will be used to determine the lab grade.

LAB REPORTS: Reports are due at the next regular session after each completed experiment. You will work with lab partners in taking data, but you must prepare the report by yourself.

PREPARATION FOR THE LABORATORY: Each student MUST read the appropriate lab before coming to lab each week and make an effort to understand the relevant material. Bring your Manual to each lab session.

LAB LOCATION: Labs 2-9 will be performed in 312B Bonner Hall. We will update you on the place for the first lab.

EACH LAB EXPERIMENT TAKES APPROXIMATELY 1.5 HOURS.

The lab schedule will be arranged to accommodate each student if preferable time will be not the time of class schedule.

EXPERIMENTS:

Nine lab experiments will be carried out by all students. Students will work in groups of two. Students with disabilities or special requirements (e.g. military service) should inform the TA as early as possible.

Experiment 1: Propagation of Errors
Experiment 2: Quantum yard stick – measurement of Planck's constant
Experiment 3: Diffraction of light by a double-slit – one photon at a time
Experiment 4: Photoelectric effect: waves behaving as particles
Experiment 5: Atomic spectra; hydrogen Balmer lines; sodium D-doublet
Experiment 6: Photoluminescence from InP quantum dots
Experiment 7: Introduction to Atomic Force Microscopy (AFM)
Experiment 8-9: Study of InAs quantum dots and Si nanowires using AFM

Short description of the experiments are given below.

Experiment 1: *Propagation of Errors*

In this experiment students will explore how the uncertainty σ_x of parameter x determines the uncertainty σ_y of parameter y if we know the dependence of y on x (we assume that we know the function $y(x)$). The second topic of this lab examines how the uncertainty σ_y of parameter y that is determined by N parameters $x_1, x_2, \ldots, x_N$ (we assume that we know the function $y(x_1, x_2, \ldots, x_N)$) depends on the uncertainties σ_{x1}, σ_{x2}, …, σ_{xN} of the parameters $x_1, x_2, \ldots, x_N$. These concepts are demonstrated in a simple optical experiment that involves a lens whose focal length f will be determined by measuring the object-lens distance o and the image-lens distance i.

Experiment 2: *Quantum yard stick – measurement of Planck's constant*

The students will learn how to distinguish whether a physical system is macroscopic or microscopic. The first step is to measure the appropriate yard stick, Planck's constant, h. Rather than use the photoelectric effect, the students will use a series of light-emitting diodes (LEDs), which emit in the visible range. The students will record the I−V characteristics of these LEDs, and from these characteristics determine the threshold voltage, V_o, at which each LED starts emitting light. The threshold voltage V_o is related to the band gap E_g of a semiconductor material of the LED as:

$$eV_{\mathrm{o}} = E_g \,. \tag{1}$$

The students will use a gating spectrometer to measure the average wave length λ at which the LED emits. This is related to the band gap as:

$$E_g = hc/\lambda \,. \tag{2}$$

If we combine these two equations we get:

$$1/\lambda = (e/hc)V_0 \,. \tag{3}$$

A plot of $1/\lambda$ versus V yields a straight line and allows students to determine Planck's constant, h. As a part of the lab report the students will be asked to use Planck's constant as a yard stick to classify systems as microscopic or macroscopic.

Experiment 3: *Diffraction of light by a double-slit – one photon at a time*

The students will study double nature of light particle photon. The specially designed two-slit diffraction experiment allows students to study interference of photons in the regime, under which, on the average, only one photon passes through the slits. Students will be able to observe the process of building up the interference pattern. This experiment is analogous to Tonomura's experiment. The difference is instead of studying wave-particle duality of an electron, students will study wave nature of the light particle – photon in real time.

Experiment 4: *Photoelectric effect: waves behaving as particles*

The students will repeat the famous experiment carried out by Heinrich Hertz and interpreted by Albert Einstein in 1905. The most striking aspect of this experiment is that photons (particles of light) with energy less than the work function of the cathode metal cannot extract electrons from it.

Experiment 5: *Atomic spectra; hydrogen Balmer lines; sodium D-doublet*

The students will use a grating spectrometer to measure the wavelengths of two sources: a) Hydrogen lamp: The students will record the wavelengths of the Balmer lines of hydrogen. The measured values will be compared to the calculated wavelengths using the Bohr's model of hydrogen atom. b) Sodium lamp: The students will record the yellow D-line from sodium and resolve its two components that are associated with the 3p electron state, which is split into the $P_{3/2}$ and $P_{1/2}$ states due to the spin-orbital coupling. The students will measure the energy separation of the two components of the D-line and compare it with the value in the literature.

Experiment 6: *Photoluminescence from InP quantum dots*

In this experiment the students record the emission spectra from InP QDs excited with a UV diode and evaluate the radii of QDs from their emission spectra.

Experiment 7: *Introduction to Atomic Force Microscopy (AFM)*

In this experiment students will learn the basic principles of operation of Atomic Force Microscope (AFM). Using this knowledge they will study the surface of the silicon oxide microstructure. They will obtain with the help of AFM the images of the periodic structure of the holes in the silicon oxide layer, including three-dimensional image of the silicon oxide surface layer, and measure the thickness of the microstructure.

Experiment 8-9: *Study of InAs quantum dots and Si nanowires using AFM*

The students will use the knowledge of AFM operation gained in the seventh lab to characterize the sizes and shapes of InAs quantum dots and Si nanowires.