Abstract
Quantum mechanics is the basis for understanding physical phenomena on the atomic and nanometer scale. There are numerous applications of quantum mechanics in biology, chemistry and engineering. Those with significant economic impact include semiconductor transistors, lasers, quantum optics and photonics. As technology advances, an increasing number of new electronic and opto-electronic devices will operate in ways that can only be understood using quantum mechanics. Over the next twenty years fundamentally quantum devices such as single-electron memory cells and photonic signal processing systems will become commonplace. The purpose of this course is to cover a few selected applications and to provide a solid foundation in the tools and methods of quantum mechanics. The intent is that this understanding will enable insight and contributions to future, as yet unknown, applications.

Prerequisites
Mathematics:
A basic working knowledge of differential calculus, linear algebra, statistics, and geometry.
Computer skills:
An ability to program numerical algorithms in MATLAB or similar language and display results in graphical form.
Physics background:
Should include a basic understanding of Newtonian mechanics, waves, and Maxwell’s equations.
Introduction: Lectures 1 - 5

Lecture 1-2

REVIEW OF CLASSICAL CONCEPTS
Extended discussion to include material from the book “Essential classical mechanics for device physics”.
The linear and nonlinear oscillator
Electromagnetism
Mechanical model of light-matter interaction due to Lorentz.

Lecture 3

TOWARDS QUANTUM MECHANICS – PARTICLES AND WAVES
Diffraction, interference, and correlation functions for light
Black-body radiation and evidence for quantization of light
Photoelectric effect
THE PHOTON PARTICLE
The existence of the photon particle
The photon at a beam splitter
Secure quantum communication

Lecture 4-5

WAVE-PARTICLE DUALITY
The link between quantization of photons and quantization of other particles
Diffraction and interference of electrons
When is a particle a wave?
THE SCHRÖDINGER WAVE EQUATION
The wave function description of an electron of mass $m_0$ in free-space
The electron wave packet and dispersion
The Bohr model of the hydrogen atom
Calculation of the average radius of an electron orbit in hydrogen
Calculation of energy difference between electron orbits in hydrogen
Periodic table of elements
Crystal structure
Three types of solid classified according to atomic arrangement
Two-dimensional square lattice, cubic lattices in three-dimensions
Electronic properties of semiconductor crystals
The semiconductor heterostructure

Using the Schrödinger wave equation: Lectures 6 - 7

Lecture 6-7

INTRODUCTION
The effect of discontinuities in the wave function and its derivative
WAVE FUNCTION NORMALIZATION AND COMPLETENESS
INVERSION SYMMETRY IN THE POTENTIAL
Particle in a one-dimensional square potential well with infinite barrier energy
NUMERICAL SOLUTION OF THE SCHRÖDINGER EQUATION
Matrix solution to the discretized Schrödinger equation
Nontransmitting boundary conditions. Periodic boundary conditions

**CURRENT FLOW**
Current flow in a one-dimensional infinite square potential well
Current flow due to a traveling wave

**DEGENERACY IS A CONSEQUENCE OF SYMMETRY**
Bound states in three-dimensions and degeneracy of eigenvalues

**BOUND STATES OF A SYMMETRIC SQUARE POTENTIAL WELL**
Symmetric square potential well with finite barrier energy

**TRANSMISSION AND REFLECTION OF UNBOUND STATES**
Scattering from a potential step when effective electron mass changes
Probability current density for scattering at a step
Impedance matching for unity transmission

**PARTICLE TUNNELING**
Electron tunneling limit to reduction in size of CMOS transistors

**THE NONEQUILIBRIUM ELECTRON TRANSISTOR**

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Scattering in one-dimension: The propagation method: Lectures 8 - 10

**Lecture 8**

**THE PROPAGATION MATRIX METHOD**
Writing a computer program for the propagation method

**TIME REVERSAL SYMMETRY**
CURRENT CONSERVATION AND THE PROPAGATION MATRIX

**Lecture 9**

**THE RECTANGULAR POTENTIAL BARRIER**
Tunneling

**RESONANT TUNNELING**
Localization threshold
Multiple potential barriers

**THE POTENTIAL BARRIER IN THE δ-FUNCTION LIMIT**

**ENERGY BANDS IN PERIODIC POTENTIALS: THE KRONIG-PENNY POTENTIAL**
Bloch’s theorem
Propagation matrix in a periodic potential
Real and imaginary band structure

**Lecture 10**

**THE TIGHT BINDING MODEL FOR ELECTRONIC BAND STRUCTURE**
Nearest neighbor and long-range interactions
Crystal momentum and effective electron mass

**USE OF THE PROPAGATION MATRIX TO SOLVE OTHER PROBLEMS IN ENGINEERING**

**THE WKB APPROXIMATION**
Tunneling
**RELATED MATHEMATICS:** *Lecture 14 - 15*

Lecture 14-15

**ONE PARTICLE WAVE FUNCTION SPACE**
**PROPERTIES OF LINEAR OPERATORS**
   - Hermitian operators
   - Commutator algebra

**DIRAC NOTATION**

**MEASUREMENT OF REAL NUMBERS**
   - Time dependence of expectation values. Indeterminacy in expectation value
   - The generalized indeterminacy relation

**THE NO CLONING THEOREM**

**DENSITY OF STATES**
   - Density of states of particle mass $m$ in 3D, 2D, 1D and 0D
   - Quantum conductance
   - Numerically evaluating density of states from a dispersion relation
   - Density of photon states

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**The harmonic oscillator:** *Lectures 17 - 18*

Lecture 17

**THE HARMONIC OSCILLATOR POTENTIAL**
**CREATION AND ANNIHILATION OPERATORS**
   - The ground state. Excited states

**HARMONIC OSCILLATOR WAVE FUNCTIONS**
   - Classical turning point

**TIME DEPENDENCE**
   - The superposition operator. Measurement of a superposition state

Lecture 18

   - Time dependence in the Heisenberg representation
   - Charged particle in harmonic potential subject to constant electric field

**ELECTROMAGNETIC FIELDS**
   - Laser light
   - Quantization of an electrical resonator
   - Quantization of lattice vibrations
   - Quantization of mechanical vibrations

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**Fermions and Bosons:** *Lecture 19 - 20*

Lecture 19

**INTRODUCTION**
   - The symmetry of indistinguishable particles. Slater determinant
   - Pauli exclusion principle. Fermion creation and annihilation operators – application to tight-binding Hamiltonian

**FERMI-DIRAC DISTRIBUTION FUNCTION**
   - Equilibrium statistics
Writing a computer program to calculate the chemical potential and Fermi-Dirac distribution at finite temperature

**BOSE-EINSTEIN DISTRIBUTION FUNCTION**

**CURRENT AS FUNCTION OF VOLTAGE BIAS**

Semiconductor heterostructure diode structures in the depletion approximation.
Metal-insulator-metal.
Reduced dimensions

**Lecture 20**

**PHOTON FOCK STATES**

The Mandel effect
n-photons at a beam splitter
n-photons at a FP resonator

**THE MANDEL EFFECT**

Dual photon source
Fiber-optic beam splitter and delay line
Photon counting and correlation

**Time dependent perturbation theory and the laser diode:** *Lectures 21 - 23*

**Lecture 21**

**FIRST-ORDER TIME-DEPENDENT PERTURBATION THEORY**

Abrupt change in potential
Time dependent change in potential

**CHARGED PARTICLE IN A HARMONIC POTENTIAL**

**FIRST-ORDER TIME-DEPENDENT PERTURBATION**

**FERMI’S GOLDEN RULE**

**IONIZED IMPURITY ELASTIC SCATTERING RATE IN GaAs**

The coulomb potential. Linear screening of the coulomb potential
Correlation effects in position of dopant atoms
Calculating the electron mean free path

**Lecture 22**

**EMISSION OF PHOTONS DUE TO TRANSITIONS BETWEEN ELECTRONIC STATES**

Density of optical modes in three dimensions
Light intensity
Background photon energy density at thermal equilibrium
Fermi’s golden rule for stimulated optical transitions
The Einstein A and B coefficients
Occupation factor for photons in thermal equilibrium in a two-level system
Derivation of the relationship between spontaneous emission rate and gain

**THE SEMICONDUCTOR LASER DIODE**

Spontaneous and stimulated emission. Optical gain in a semiconductor. Optical gain in the presence of electron scattering

**DESIGNING A LASER CAVITY**

Resonant optical cavity. Mirror loss and photon lifetime
The Fabry-Perot laser diode. Rate equation models
Lecture 23

**NUMERICAL METHOD OF SOLVING RATE EQUATIONS**
The Runge-Kutta method. Large-signal transient response. Cavity formation

**NOISE IN LASER DIODE LIGHT EMISSION**
Effect of photon and electron number quantization
Langevin and semiclassical master equations

**QUANTUM THEORY OF LASER OPERATION**
Density matrix
Single and multiple quantum dot, saturable absorber

**Time independent perturbation theory:** *Lectures 24*

Lecture 24

**NON-DEGENERATE CASE**
Hamiltonian subject to perturbation $W$
First-order correction. Second order correction
Harmonic oscillator subject to perturbing potential in $x$, $x^2$ and $x^3$

**DEGENERATE CASE**
Secular equation
Two states
Perturbation of two-dimensional harmonic oscillator
Perturbation of two-dimensional potential with infinite barrier

**Angular momentum, the hydrogenic atom, and bonds:** *Lectures 25 - 26*

Lecture 25

**ANGULAR MOMENTUM**
Classical angular momentum
The angular momentum operator
Eigenvalues of the angular momentum operators $L_z$ and $L^2$
Geometric representation

**SPHERICAL HARMONICS AND THE HYDROGEN ATOM**
Spherical coordinates and spherical harmonics
The rigid rotator
Quantization of the hydrogenic atom
Radial and angular probability density

Lecture 26

**ELECTROMAGNETIC RADIATION**
No eigenstate radiation
Superposition of eigenstates
Hydrogenic selection rules for dipole radiation
Fine structure

**BONDS.**
The hydrogen molecule ion.
The hydrogen molecule covalent bond
Valence bond description.
Molecular orbital description
The ionic bond