Course Proposal

Department of Electrical Engineering

Indian Institute of Technology Kanpur

1. **Course Number:** EE6XX
2. **Course Title:** Nanoelectronics
3. **Prerequisite:** There is no official pre-requisite for the course.
4. **Course Credits:** (3-0-0-0) [9]
5. **Course Duration:** Full Semester
6. **Proposing Instructor:** Dr. Rik Dey, email: rikdey@iitk.ac.in
   Other faculty members who may be interested in teaching the course:
   Dr. Amit Verma, Dr. Rituraj, Dr. Arnab Bose
7. **Other departments who may be interested in the proposed course:** Physics, MSE, SEE
8. **Course Type:** PG, 3rd & 4th year UG, Open Elective
9. **Course Description:** The course will provide a comprehensive introduction and basic understanding of the principles, devices, and technologies of nanoelectronics, which is the foundation of modern information processing and next-generation electronic systems. This course will explore the physical concepts that govern electronic transport at the nanoscale, where quantum mechanical behaviour, such as quantum confinement, quantum mechanical transmission and quantum tunneling, dominate over the classical behavior. The topics in this course include scaling limits of conventional devices, low-dimensional systems such as quantum wells, quantum wires and quantum dots, density of states and carrier statistics in such low-dimensional systems, ballistic vs. diffusive transport formalisms, mesoscopic transport and device modeling approaches. The course will explain the fundamentals of nanoelectronics and mesoscopic physics, emphasizing both fundamental physics and practical applications, bridging concepts of quantum mechanics, solid-state physics, and device engineering. By the end of the course, students will gain a strong foundation to analyze, model, and design nanoscale devices, and also will develop insight into ongoing challenges and opportunities in nanoelectronics research and applications.

10. Course Contents:

Content Outline of Lectures	**Lect.**
Introduction: Importance of the course and relevance to modern electronics	1
Basics of quantum mechanics: Schrodinger equation, one-dimensional potentials: infinite square well, delta function, finite square well, triangular well	4
Quantum transmission and tunneling: bound states vs. scattering states, probability conservation, reflection and transmission, tunneling, transmission matrix, scattering matrix, resonance transmission, resonance tunneling, transfer matrix method	5
Electronic band-structure: Born-Oppenheimer approximation, independent electron approximation and self-consistent field, periodic potential and Bloch theorem, one-dimensional Kronig-Penney model, time-independent perturbation theory and nearly free electron model, linear combination of atomic orbitals and tight-binding method, k.p perturbation theory, envelop function and effective mass approximation	6

Quantum confinement: Heterostructures & superlattices, low-dimensional systems: quantum wells, quantum wires, quantum dots, density of states in low dimensions, carrier statistics in low dimensions, Fermi-Dirac integrals, quantum capacitance	4
Semiclassical picture of transport: Drude model of transport, scattering as Poisson process, drift-diffusion equation, transport in metals vs. semiconductors, Ohm's law, generalized Einstein-Smoluchowski relation, local-equilibrium & quasi-Fermi level, Hall effect and different effective masses	4
Ballistic transport: Ballistic vs. diffusive conductor, new Ohm's law, conductance quantization, density of modes in low dimensions, current from quasi-Fermi levels and Landauer formula, voltage drop and contact resistance, ideal voltage probe, ideal vs. non-ideal contacts, heat dissipation in the conductor and contacts, Landauer-Buttiker formalism for multi-terminal devices	6
Boltzmann Transport Equation (BTE): Liouville's theorem to BTE, collision integral in the BTE, microscopic reversibility & principle of detailed balance, relaxation time approximation, analytical solution method of BTE with example, drift-diffusion equation from BTE, diffusive to ballistic limit of BTE	5
Nanoelectronics Device Modeling: Resonant tunneling diode, quantum confinement in metal-oxide-semiconductor (MOS) capacitor and effect of quantum capacitance, single electron charging and Coulomb blockade, transport in ballistic nano-transistor, smart-contact devices (p-n junction diode, spin-valve, magnetic tunnel junctions)	3
Course overview and future directions	1
Total no. of lectures	**39**

Nanoelectronics Modeling through Simulations:

As part of homework and/or project, the student will also learn the applications of theoretical concepts (which they will learn in lectures as mentioned above) through numerical modeling and simulation exercises for each of the above-mentioned topic as outlined below.

Basics of quantum mechanics: Numerical solution of the time-independent Schrodinger equation in one-dimensional system using spatial discretization scheme or shooting method for infinite square well, finite square well, truncated triangular well potentials.
Quantum transmission and tunneling: Simulation of reflection and transmission from step and barrier potentials, quasi-bound states and connection to bound states for potential well, resonance transmission and resonance tunneling
Electronic band-structure: Self-consistent solution of Schrodinger equation considering self-consistent field, numerical solution of one-dimensional Kronig-Penney model for various types of binding potentials, calculation of band structure for 1D and 2D systems, e.g. mono-layer and bilayer graphene, carbon nanotubes, transition metal dichalcogenides, etc.
Quantum confinement: Simulation of density of states, carrier statistics, and carrier concentrations in metals and semiconductors for various dimensions (0D, 1D, 2D, 3D); simulation and/or numerical modeling of 1D heterostructure, numerical solution of coupled Schrodinger and Poisson equation and consideration of quantum confinement

<u>Semiclassical picture of transport:</u> 2D simulation of diffusive transport with scattering, simulation/numerical solution of 1D drift-diffusion equation, minority carrier diffusion, etc.
<u>Ballistic transport:</u> Simulation of density of modes in various dimensions, numerical model for Landauer transport and transition from ballistic to diffusive limit, simulation/modeling of conductance quantization, simulation of voltage drops and heat dissipation
<u>Boltzmann Transport Equation (BTE):</u> Numerical solution of BTE, solution of BTE in 2D and 3D from the ballistic to diffusive limits, origin of contact resistance in BTE model
<u>Nanoelectronics Device Modeling:</u> Numerical modeling/simulation of the devices: resonant tunneling diode, MOS capacitor, ballistic nano-transistor, single electron transistor, spin transport in spin-valve, magnetic tunnel junctions, etc.

11. References:

1. *The Physics of Low-Dimensional Semiconductors: An Introduction,* John H. Davies, Cambridge University Press, 1998.
2. *Quantum Physics of Semiconductor Materials and Devices*, Debdeep Jena, Oxford University Press, 2022.
3. *Quantum Transport: Atom to Transistor*, Supriyo Datta, Cambridge University Press, 2005.
4. *Lessons from Nanoelectronics: A New Perspective on Transport*, Supriyo Datta, World Scientific, 2012.
5. *Electronic Transport in Mesoscopic Systems*, Supriyo Datta, Cambridge University Press, 1997.
6. *Fundamentals of Carrier Transport*, Mark Lundstrom, 2002.

12. Past Teaching Experience of the Proposing Instructor on Related Topic:

The proposing instructor has previously organized two short-term courses as given below:

Organizer	Date	Course Title	Place
ATAL Academy Faculty Development Program	02-06 August, 2021	Physics of Nanoelectronics	IIT Kanpur (Online)
Quality Improvement Program, Center for Continuing Education	15-20 March, 2021	Transport in Nanoelectronics	IIT Kanpur (Online)

Rik Dey

Date: 01/10/2025 Signature of the Proposer

Convenor, DPGC
Department of Electrical Engineering

Chairperson, SPGC
IIT Kanpur