Indian Institute of Technology, Kanpur
Department of Electrical Engineering

Proposal for a New Course

1. Course No: EE6XX

2. Course Title: Introduction to Spintronics

3. Per Week Classes: 2 Lectures (L), 0 Tutorial (T), 0 Laboratory (P), 0 Additional Hours (A),

Credits (2L+T+P+A): **9 credits**

4. Proposing Department: Department of Electrical Engineering

Duration of Course: Full Semester

Other Departments which may be interested: Physics, MSE.

Other faculty members interested in teaching the proposed course: Prof. Rik Dey (EE)

Proposing Instructor: Prof. Arnab Bose

6. Course Description:

A) Objectives:

Electron transport has long been central to microelectronics and VLSI. Each electron also carries spin angular momentum, which can be harnessed for data storage and processing. This course introduces the key principles of spin transport in heterostructures, providing students in Electrical Engineering and related disciplines with the foundation needed to pursue research in this area. Beginning with a review of essential quantum mechanics concepts, the course will gradually introduce the properties of quantum materials and devices, including the coupling among charge, spin, and orbital degrees of freedom and their interactions with magnons and phonons.

The course is organized into four modules. The first introduces the essential concepts of quantum mechanics that provide the foundation for the course and will span 6–7 lectures. The second covers the fundamentals of nanomagnetism over 6–7 lectures. The third focuses on the core concepts of spintronics, including spin currents, spin torques, and spin-torque-induced magnetization dynamics. Topics include spin-torque ferromagnetic resonance, magnetization switching, and oscillations, covered over 8–9 lectures. The fourth module covers advanced topics, including spin–orbit coupling effects, spintronic devices, and their applications.

In addition to standard homework exercises, students will undertake four mini-projects involving macrospin and quantum simulations. These projects will help them connect the theoretical concepts with physical behaviour and develop practical simulation skills. Students will also deliver a seminar and submit a report on assigned research topics. The course is designed for students with limited prior exposure to spintronics, guiding them from its basic principles to advanced concepts and practical applications.

B) Contents (preferably in the form of 5 to 10 broad titles):

Lectures	***Topics***

1	***Mod-1. (Fundamentals of Quantum Mechanics)*** ***Mod1.0Introductory class*** Overview of spin electronic devices. Scope and aim of this course, syllabus. Brief history of quantum mechanics
2	***Mod1.1*** ***Fundamentals of Linear Vector Space*** Linear vector space continues. Concept of operator. Elements of the operator. Hermitian and anti-Hermitian operators. Some examples. Unitary operators. Important identities. Eigenvalue problem. Finding eigenvalues and eigenvectors of Hermitian operators. Diagonalization. Simultaneous diagonalization of two Hermitian operators.
3	***Mod1.2*** ***Postulates of QM beginning with the Schrödinger equation*** Postulates of QM. Schrödinger equation with time evolution Etc. Time evolution of operators. Practice problems (Normalization of wave functions, Current operator, Ehrenfest theorem). Heisenberg's uncertainty principle, etc.
4	***Mod1.3*** ***Application of the time-independent Schrödinger equation (TISE)*** Problem solving. TISE case studies for various V(x). (1) infinite potential well, (2) finite potential barrier→tunneling, (3) free particle → wave packets
5	***Mod1.3*** ***Application of the time-independent Schrödinger equation (TISE)*** Simple Harmonic Oscillator ***Mod1.4*** ***Angular momentum***
6	***Mod1.5*** ***Solution of SE in 3d spherical system*** H-atom problem. Concept of orbitals and orbital angular momentum
7	***MAJOR QUIZ-1*** Solve the quiz problems
	Mod2. Spin and exchange interaction: Emergence of magnetism
8	***Mod2.1: Spin operators, magnetic moment and Larmor precession*** Spin operators: S^2, $S_{x,y,z}$, $S_{\pm}$, $S_{\theta,\phi}$ eigenvalues, eigenstates. Pauli's matrices. HW problems QM description of spin and orbital angular magnetic moment, Bohr magneton Spin in the magnetic field. Zeeman splitting of the energy levels. Expectation values of the different components of spin. Larmor precession. Solution of the coupled equation for magnetization dynamics.
9	***Mod2.2*** ***Addition of spin angular momentum in two spin-1/2 systems.*** Emergence of singlet/triplet states. Solving problems in class. Beginning the two-particle system
10	***Mod2.3*** ***Two-particle system*** Two-particle joint wave functions: symmetric and antisymmetric wave functions for Bosons and Fermions. Energies of the 2-particle system → onsite energy, **exchange energy**. ***Two case studies. (1) He-atom and (2) H2 molecule*** (Not a detailed derivation, but rather the essence of various exchange integrals and their signs relevant to FM and AFM ordering.)

11	***Mod.2.4*** ***Magnetism basics*** Atoms to solids, Energy bands, and DOS. Bandwidth, hoping integral, and overall trend of magnetism in 3d, 4d, 5d metals. Environments in solids, crystal field splitting (e_g, t_{2g} bands) and orbital quenching. Types of exchange interactions: super-exchange, double exchange, exchange from conduction electrons, RKKY, DMI, etc. Magnetic zoo. Stonner criterion and band magnetism of Fe, Co, Ni
12	***Mod.2.4*** ***Magnetism basics*** Revision of the last class. Pauli's paramagnetism. Stoner criterion and band magnetism of Fe, Co, Ni. Spin-split bands and Fermi surfaces and their influence on transport ***Mod2.5*** ***Magnetic energy and anisotropy*** Dipole moment and energies. Shape anisotropy and associated energies. Coercivity, demagnetization field. Interfacial magnetic anisotropy. Perpendicular magnetic anisotropy (PMA) and its technological application.
13	***Mod2.6 Field-induced magnetization dynamics*** Introducing the LLG equation. Stable states by solving the LLG. Solution of LLG for DC magnetic field→magnetization dynamics for switching by the DC magnetic field. Solution of LLG with RF excitation → FMR. Susceptibility tensor.
	Mod.3. Spin current, spin transport and magnetization dynamics
14	***Mod3.1 Spin-dependent diffusive transport*** Spin-dependent conductivity and electrochemical potential. Definition of spin accumulation and spin transport. Valet-Fert Equation. Spin diffusion model. Case-1: Derivation of the GMR effect using the Valet Fert equations. Two-channel resistor model of GMR.
15	***Mod3.1 Spin-dependent diffusive transport*** Case-2: Injection of spin current from FM to NM. Conductivity mismatch problem. The essence of high interfacial resistance is the tunnelling mechanism. Charge-to-spin interconversion by explaining non-local spin-valve devices.
16	***Mod3.2. Spin-dependent tunnelling*** Recap of basic tunnelling by solving the SE equation. "Transfer Hamiltonian model" (Julier model). Modelling of TMR with DOS. Real TMR devices: Magnetic Tunnel Junctions (MTJs). Experimental aspects of the growth and fabrication of MTJ. Starting with the "free electron model".
17	***Mod3.2. Spin-dependent tunnelling*** Completing the free electron model. Essence of the free electron model: new definition of effective polarization, effect of potential barrier, wave vector matching and spin filtering on TMR. Transfer Hamiltonian model vs the free electron model. ***Finding spin-polarization in superconductor/tunnel barrier ferromagnet heterostructures***
18	***Mod3.3 Current-induced magnetization dynamics*** Fundamentals. Concept of spin-transfer torque (STT). STT-induced magnetization dynamics: criteria for Switching, oscillation of in-plane magnet.
19	***Mod3.3 Current-induced magnetization dynamics*** Action of RF spin current → ST-FMR, susceptibility tensors for spin Brief discussion on different mechanisms for spin current generation e.g. longitudinal, transverse spin current, spin Hall effect, thermally driven spin current, spin pumping, etc. Technological evolution and the essence of PMA.

20	***MAJOR QUIZ 2*** Solve the quiz problems
21	***Mod3.3 Current-induced magnetization dynamics*** J_S-induced PMA switching, Spin-torque ferromagnetic resonance (ST-FMR)
	Mod.4. Modern Spintronics devices
22	***Mod 4.1-Spin-orbit coupling and its implication in SSD (SHE, REE etc.)*** Introduction, spin-orbit coupling (SOC) at atomic level, SOC in solids→Rashba, Dresselhaus, etc. Introducing Berry curvature through adiabatic approx.
23	***Mod4.1. continuing*** Symmetry arguments for the existence of Berry curvature, band-anti crossing, intrinsic spin Hall effect, AHE. Extrinsic contribution to spin Hall effect
24	***Mod-4.2. Recent experiments*** Charge to spin interconversion: various cases, including SHE and ISHE in spin pumping, spin Seebeck experiments, etc.
25	***Mod-4.2. Recent experiments*** Introducing the Quantum Hall effect, Josephson Junction, and superconducting qubits.
26	***Summary, outlook, and doubt clearing/Project-Seminar***

C) Pre-requisites: Strong interest in learning new things

7. Recommended books

- Quantum Mechanics, D. J. Griffiths
- Quantum Mechanics, R. Shankar
- Introduction to Magnetic Materials, B. D. Cullity and C. D. Graham
- Magnetism in Condensed Matter by Stephen Blundell
- Nanomagnetism and Spintronics, Teruya Shinjo
- Introduction to Spintronics, S. Bandyopadhyay
- Spin Current, Sadamichi Maekawa, Sergio O. Valenzuela, Eiji Saitoh, Takashi Kimura
- Recent papers and review articles as referred to in the lecture slides.
- Reference books: Lessons from Nano Electronics, Quantum Transport, Supriyo Datta and extended class notes

Dated: 09.10.2026 Proposer: Arnab Bose

Dated: _____ DUGC/DPGC Convener: _____

This course is approved/not approved

Chairman, SUGC/SPGC

Dated: _____