PHY598CMX: Condensed Matter Physics T Th 2:30 PM- 3:50 PM
Room: Zoom

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Office Hours: (TLH) Tuesdays 11:00 AM at ESB 2115 and possibly via appointment.

Recommended Textbook: *Modern Condensed Matter Physics* by S. Girvin and K. Yang

Prerequisites: PHYS 427; PHYS 580, 560. If you haven't had 560 you should at least have a strong familiarity with band-theory.

Course Objectives: The goal of this course is to set the foundation for future research in condensed matter physics especially in the modern theory of electronic structure. A detailed, but ambitious course outline can be found on the next two pages.

Anti-Racism and Inclusivity Statement for Inclusion in Course Syllabi: The Grainger College of Engineering is committed to the creation of an anti-racist, inclusive community that welcomes diversity along a number of dimensions, including, but not limited to, race, ethnicity and national origins, gender and gender identity, sexuality, disability status, class, age, or religious beliefs. The College recognizes that we are learning together in the midst of the Black Lives Matter movement, that Black, Hispanic, and Indigenous voices and contributions have largely either been excluded from, or not recognized in, science and engineering, and that both overt racism and micro-aggressions threaten the well-being of our students and our university community. The effectiveness of this course is dependent upon each of us to create a safe and encouraging learning environment that allows for the open exchange of ideas while also ensuring equitable opportunities and respect for all of us. Everyone is expected to help establish and maintain an environment where students, staff, and faculty can contribute without fear of personal ridicule, or intolerant or offensive language. If you witness or experience racism, discrimination, micro-aggressions, or other offensive behavior, you are encouraged to bring this to the attention of the course director if you feel comfortable. You can also report these behaviors to the Bias Assessment and Response Team (BART) (https://bart.illinois.edu/). Based on your report, BART members will follow up and reach out to students to make sure they have the support they need to be healthy and safe. If the reported behavior also violates university policy, staff in the Office for Student Conflict Resolution may respond as well and will take appropriate action.

Other Statements: For statements on sexual misconduct, academic integrity, religious observances, disability-related accomodations, and FERPA please see here: https://wiki.illinois.edu/wiki/display/ugadvise/Syllabus+Statements

1 [Tentative]Course Outline: PHYS 598 CMX

1. Advanced Semiconductor Modeling
   - From tight-binding to $k \cdot P$ theory
   - Low-energy Hamiltonians for common semi-conductors (Si, III-V's, SSH chain)
   - From $k \cdot P$ theory to tightbinding
   - Band-Projection using Lowdin Perturbation Theory
   - Kane model reduced to conduction band and Luttinger models
   - Dirac model reduced to Schrodinger
   - Dresselhaus Spin-Orbit Coupling
2. Heterostructures and Quantum Confinement
   - Interfaces and work function
   - Confinement, envelope function approximation, and quantum well subbands
   - Rashba effect from inversion symmetry breaking; Persistent spin helix
   - Quantum wires: quantized conductance, Rashba+Zeeman, Rashba+Zeeman+Superconductivity
   - Quantum Dots: random matrix theory, single-electron transistor, Coulomb blockade
3. Topological Things Part 1
   - Landau levels: Integer Quantum Hall effect
   - IQHE:Bulk Hall effect, guiding centers, and edge states
   - IQHE:Flux-charge attachment, Chern number, disordered systems
   - IQHE: Lattice model (Hofstadter)
   - IQHE:Peierls substitution, edge states, flux-threading/Laughlin pumping argument
   - IQHE:Chiral modes, fermion doubling theorem
   - IQHE:Landauer-Buttiker transport in 2-terminal and 4-terminal devices
   - Chern Insulator: Quantum Hall Effect Without Magnetic Field
   - CI:Continuum Dirac model, 1/2 Hall conductance
   - CI:Domain Wall edge states
   - CI: Lattice Dirac Model, Band inversion, Chern number, band representations
   - CI: Superconductor Proximity and Chiral Majorana Fermions
   - Quantum Spin Hall Insulator:BHZ lattice model
   - QSH:Helical Edge states, Z_2 invariant, Kramers' degeneracy
   - QSH:Band inversion, band representations, "spin"-Hall effect, spin-charge separation
   - QSH: Superconductor proximity, helical Majorana modes
   - 3D Topological Insulator: lattice model, surface states, π-Berry phase
   - 3DTI: fermion doubling, Z_2-stability of surface states
   - 3DTI: Surface magnetic domain wall, chiral modes
   - 3DTI: Surface superconductor proximity effect, Fu-Kane superconductor, vortices
   - 3DTI: Magnetic/superconductor domain wall
   - 3DTI: Axion electrodynamics, surface Hall effect
   - Topological Crystalline insulators: basic concepts and experiments
4. Topological Things Part 2
   - Stacking topological systems

- 1D to 2D: Stacking SSH chains, weak topological insulator, stability requirements
- 1D to 2D: Dirac semimetal, T-breaking, inversion-breaking gaps, stability requirements
- 1D to 2D: Charge polarization, edge states
- 2D to 3D: Stacking Chern Insulators, weak topological insulator,
- 2D to 3D: Weyl semi-metal, anomalous Hall effect, CDW gapping term, stability requirements
- 2D to 3D: Fermi arc states, monopole charge/fermion doubling, momentum-space "phase transition"
- Dislocation bound states

5. Green Functions and Self-Energies
   - Green functions of coupled oscillators [TLH]
   - Green functions of matrix tight-binding models [TLH]
   - Self-energies generated by integrating out leads in transport setups [TLH]
   - Self-energies from coupling to phonons [VM]
   - Experimental Consequences [VM]
6. Detailed Experimental Techniques
   - TEM [VM]
   - Neutron Scattering [VM]
   - SdH and dH-vA [VM/TLH]
   - ARPES
   - STM
   - EELS
   - ...
7. Intro to Strongly Correlated Systems and Families of Materials
   - Fermi-Liquid Theory [TLH]
   - General definitions of metals, insulators, quantum metric and localization. Lieb-Schultz-Mattis, and Luttinger theorems [TLH]
   - Mermin-Wagner Theorem [TLH]
   - Mott Insulators [VM]
   - Kondo Effect [VM]
   - Ordered States and Instabilities: CDW, SDW [VM]
   - Twisted Bilayer Graphene [VM]
   - Atomic spin orbit coupling and splitting in semiconductors (Iridates Jeff=1/2 bands)
   - Rashba on surfaces of Au