COURSE CONTENT FOR PH7003

Academic Year	2022/2023	**Semester**	1
Course Coordinator	Assoc. Prof. Pinaki Sengupta		
Course Code	PH7003		
Course Title	Graduate Solid State Physics		
Pre-requisites	PH3101 Quantum Mechanics or equivalent and PH3102 Condensed Matter Physics I or equivalent and PHY (PPHY) or PHY (APHY) programme and CGPA 4.0 or higher		
No of AUs	4		
Contact Hours	Lecture: 39 hours; Tutorials: 12 hours (3 hr – lecture each week; 1 hr – tutorial each week)		
Proposal Date	February 2022		

Course Aims

This course aims to equip you with the advanced concepts and problem solving skills in condensed matter physics. Condensed matter systems can display a very wide variety of phenomena. As a result, condensed matter physics is characterized by a patchwork of effective models and theories that capture the behavior of electronic and lattice systems. While each effective theory provides key insight in a particular setting, together the set of model descriptions --- phenomenology --- form the core structure of the modern day understanding of electrons in solids.

This course surveys foundational phenomenology of solid state systems with an emphasis on the origin and basic techniques used to describe how electrons behave in crystals, and material responses to electric and magnetic fields. The course will provide you with an essential conceptual framework to parse fundamental electronic phenomena in crystalline materials, as well as a toolkit of effective models and approximations to perform calculations for materials.

In the second part of the course, some topics in topological band theory of electrons will be covered as a natural extension of the more fundamental contents. This will equip you with the necessary background to make a seamless transition to research in Condensed Matter Physics.

Intended Learning Outcomes (ILO)

Upon the successful completion of this course, you (as a student) would be **able to**:

Second quantization (SQ)
1. Describe and analyze quantum many body systems in the occupation number representation.

2. Construct the wavefunctions for systems of identical particles – understand the difference between fermionic and bosonic wavefunctions.

Electrons in a lattice (EL)
3. Explain the significance and calculate the attributes of electrons in crystals (such as velocity, effective mass, quasi-momentum and energy bands);

4. Compute electronic band structure for crystals and explain the significance of bands using perturbation theory;

5. Construct effective models for electronic structure using methods such as tight-binding methods and k.p theory and solve simple effective models for electronic structure (e.g., graphene);

6. Apply low-energy effective models to evaluate the single-particle properties and excitations of crystals (such as static and thermodynamic properties and dynamical and transport properties);

Mean field theory (MFT)
7. Transform interaction terms into bilinear forms in general Hamiltonians
8. Apply MFT to study spontaneously broken phases in magnetism
9. Understand Bardeen Cooper Schrieffer theory of superconductivity as an example of MFT.

Linear Response Theory (LRT)
10. Analyze the response of a quantum many body system to an external field.
11. Calculate electrical conductivity using Kubo formula.
12. Calculate polarization of a crystal using Kubo formula.

Topological band theory (TOP)
13. Calculate Berry phase of an isolated band.
14. Analyze the role of symmetries in determining electronic properties.
15. Analyze the properties of effective models for topological materials (such as its bulk wavefunction properties, scattering of electrons and topological boundary/edge states);
16. Calculate topological band structure for Haldane model; evaluate Berry phase and chiral edges states.

Course Content

Second Quantization (Bruus and Flensberg)
Second quantization – creation and annihilation operators
Quantum many body wavefunction – bosons and fermions
Fock space – Occupation number representation

Electrons in a lattice (Ashcroft and Mermin)
Bloch theorem
Tight binding model
Low-energy effective theories
Graphene

Mean Field Theory (Bruus and Flensberg)
Fluctuation from equilibrium
Hartree-Fock theory
Heisenberg model of ferromagnetism
Stoner model of metallic magnet
BCS theory of superconductivity

Linear Response Theory (Bruus and Flensberg)
Time evolution in quantum mechanics
General Kubo formula
Kubo formula for conductivity
Kubo formula for dielectric function

Topology in condensed matter (Shankar, Bernevig)
Scalar and vector potentials
Berry phase
Time reversal symmetry
Su-Schrieffer-Heeger model
Chern bands
Quantum Hall state
Haldane model
Kane-Mele model

Assessment Table

Assessment (includes both continuous and summative assessment)

Component	Course LO Tested	Related Programme LO or Graduate Attributes	Weighting	Team / Individual	Assessment Rubrics
1. Final Examination	All	Competency (1,4,5), Communication (1,2)	50%	Individual	Point-based marking
2. Mid-term test	SQ, EL and MFT	Competency (1,4,5), Communication (1,2)	30%	Individual	Point-based marking
3. Continuous Assessment: Homework Sets	All	Competency (1,3,4,5,6), Creativity, Communication (1,2)	20%	Individual	Point-based marking
Total			100%		

Formative feedback

You will receive formative feedback is given through discussion during tutorials as well as comments on your homework assignments. Further, feedback will also be provided after the midterm exam on common mistakes and difficulties in understanding core concepts.

Reading and References

1. Many-Body Quantum Theory in Condensed Matter Physics: An Introduction (Oxford Graduate Texts) by Henrik Bruus and Karsten Flensberg, Oxford University Press, 2004. ISBN-10: 0198566336
2. Solid State Physics by Neil W. Ashcroft and N.D. Mermin, Brooks Cole, 1976. ISBN-10: 8131500527
3. Topological Insulators and Topological Superconductors by Andrei Bernevig and Taylor Hughes, Princeton University Press, 2013. ISBN-10: 069115175X
4. Topological Insulators – a review by R. Shankar, arXiv.org:1804.06471

Course Policies and Student Responsibilities

Absence Due to Medical or Other Reasons

If you are sick and unable to attend your class / Mid-terms, you have to:

1. Send an email to the instructor regarding the absence and request for a replacement class and make-up mid-term.
2. Submit the original Medical Certificate* or official letter of excuse to administrator.
3. Attend the assigned replacement class (*subject to availability*) and make-up mid-term.

* The medical certificate mentioned above should be issued in Singapore by a medical practitioner registered with the Singapore Medical Association.

Academic Integrity

Good academic work depends on honesty and ethical behaviour. The quality of your work as a student relies on adhering to the principles of academic integrity and to the NTU Honour Code, a set of values shared by the whole university community. Truth, Trust and Justice are at the core of NTU's shared values.

As a student, it is important that you recognize your responsibilities in understanding and applying the principles of academic integrity in all the work you do at NTU. Not knowing what is involved in maintaining academic integrity does not excuse academic dishonesty. You need to actively equip yourself with strategies to avoid all forms of academic dishonesty, including plagiarism, academic fraud, collusion and cheating. If you are uncertain of the definitions of any of these terms, you should go to the academic integrity website for more information. Consult your instructor(s) if you need any clarification about the requirements of academic integrity in the course.

Course Instructors

Instructor	Office Location	Phone	Email
Pinaki Sengupta	SPMS-PAP-05-03		psengupta@ntu.edu.sg

Planned Weekly Schedule

Week	Topic	Course LO	Readings/ Activities
1-2	Second quantization	SQ	Lecture/Problem sets
3	Electrons in a lattice	EL	Lecture/Problem sets
4-5	Mean Field Theory	MFT	Lecture/Problem Sets
6	Linear Response Theory	LRT	Lecture/Problem sets
6	Mid-Term Test	SQ, EL, MFT, LRT	Mid-Term Test
7-13	Topological band theory	TOP	Lecture/Problem sets

Graduate Attributes

What we want our graduates from Physics and Applied Physics to be able to do:

Upon the successful completion of the PHY, APHY, PHME and PHMS programs, graduates should be able to:

Competency	1	demonstrate a rigorous understanding of the core theories and principles of physics involving (but not limited to) areas such as classical mechanics, electromagnetism, thermal physics and quantum mechanics [PHMS only] demonstrate a rigorous understanding of the core theories and principles of mathematical sciences involving (but not limited to) areas such as analysis, algebra and statistical analysis
	2	read and understand undergraduate level physics content independently;
	3	make educated guesses / estimations of physical quantities in general;
	4	apply fundamental physics knowledge, logical reasoning, mathematical and computational skills to analyse, model and solve problems;
	5	develop theoretical descriptions of physical phenomena with an understanding of the underlying assumptions and limitations;
	6	critically evaluate and distinguish sources of scientific/non-scientific information and to recommend appropriate decisions and choices when needed;
	7	demonstrate the ability to design and conduct experiments in a Physics laboratory, to make measurements, analyse and interpret data to draw valid conclusions.

Creativity	1	propose valid approaches to tackle open-ended problems in unexplored domains;
	2	

		offer valid alternative perspectives/approaches to a given situation or problem.

Communication	1	describe physical phenomena with scientifically sound principles;
	2	communicate (in writing and speaking) scientific and non-scientific ideas effectively to professional scientists and to the general public;
	3	communicate effectively with team members when working in a group.

Character	1	uphold absolute integrity when conducting scientific experiments, reporting and using the scientific results;
	2	readily pick up new skills, particularly technology related ones, to tackle new problems;
	3	contribute as a valued team member when working in a group.

Civic Mindedness	1	put together the skills and knowledge into their work in an effective, responsible and ethical manner for the benefits of society.