Nanyang Technological University
Division of Physics and Applied Physics

Academic Year	2020/21	**Semester**	1
Course Coordinator	Assoc. Prof. Pinaki Sengupta Asst. Prof. Justin Song		
Course Code	PH3102		
Course Title	Condensed Matter Physics I		
Pre-requisites	*PH1105, PH2101, and PH2103*		
No of AUs	4 AU		
Contact Hours	51 hours (3 hr – lecture; 1 hr – tutorial)		
Proposal Date	10 September 2020		

Course Aims

This course surveys foundational concepts in solid state systems including the structure of materials as well as the motion and dynamics of electrons in material systems. The course will equip students 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 simple calculations for materials. In particular, the course aims:

A. To build the basic concepts of structure and properties of crystalline solids and the collective behaviour of electrons and atoms in materials
B. To demonstrate how solid state theory is built up from a variety of experimental data
C. To acquire fundamental and qualitative understanding about different materials.
D. To build analytical skills through problem-solving
E. To provide foundational knowledge for a more advanced treatment of solid state physics

Intended Learning Outcomes (ILO)

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

Part 1
Crystal structure and X-ray diffraction (CSXRD)
1. Describe the basic characteristics of a crystal which includes the definition of Bravais lattice, the definition of Wigner-Seitz primitive cell and writing down Miller indices for the geometrical properties of the crystal.
2. Describe the idea of reciprocal space, crystal momentum and Brillouin zones.
3. Derive and show equivalence for the conditions of constructive interference of X-rays incident on crystals.
4. Explain a crystal's stability and work with various models for different crystals with emphasis on the attractive and repulsive forces in the crystal.

Lattice vibrations and phonons (LVP)
5. Develop a model of vibrations in a 1D chain of atoms arranged in a periodic array and bound together by a harmonic potential energy.
6. Solve the equations of motion to derive dispersion relation for collective lattice vibrations and identify normal modes of vibrations and their characterisation in terms of reciprocal lattice vectors.
7. Apply ideas of quantisation of normal modes to develop concept of phonons.

Specific heat of solids (SHS)

8. Interpret the experimental results of constant volume specific heat capacity of solids c_V and explain the failure of classical thermodynamics in explaining the experimentally-measured specific heat of solids.
9. Carry out the quantum explanation for the specific heat of solids, especially in contrasting the Debye's model and the Einstein's model; derive and use density of states.

Part 2

Free electron theory (FET)

10. Describe and analyse the behaviour of metals in terms of the dynamics of free electrons using both a classical Drude model as well as a quantum mechanical free electron model.
11. Compute the basic characteristics of a metal including its conductivity, Fermi surface, density, total energy, and electronic density of states.

Electrons in crystals (EIC)

12. Explain the behaviour of electronic wavefunctions in crystals and the formation of energy bands.
13. Derive and compute the value of band gaps in crystals and explain their origin.

Metals, insulators, and semiconductors (MIS)

14. Explain and identify the key differences between metals and insulators from their electronic band structure.
15. Derive the dynamics of electrons and holes, compute their effective masses, and explain their significance in transport phenomena and optical absorption of materials.
16. Describe the characteristics of semiconductors, including the chemical potential, extrinsic and intrinsic carrier concentrations, and their significance for the transport behaviour of semiconductors.
17. Explain how modern semiconductor devices work by using the p-n junction.

Course Content

Part 1

Crystal Structure and X-ray Diffraction (CSXRD)

Basic Definitions of a crystal; Bravais lattice; crystal symmetry groups
X-ray Diffraction of Crystals
Reciprocal Space, Brillouin zone; Laue and Bragg reflection
Scattering amplitudes

Lattice vibrations and phonons (LVP)

1D lattice as a chain of coupled harmonic oscillators
Deriving and solving equations of motion to obtain dispersion relations of collective modes
Introduction to reciprocal space and Brillouin zone
Diatomic chain – acoustic and optical modes

Specific heat of solids (SHS)

Boltzmann model of classical harmonic oscillators
Einstein model
Debye model – periodic (Born-von Karman) boundary conditions, density of states, Debye cut-off frequency and counting of modes.

Part 2

Free electron theory (FET)

Drude theory - Electrons as a gas of classical charged particles in electric and magnetic fields
Quantum theory – Fermi-Dirac statistics, electronic density of states, Fermi surface, density, total energy

Electrons in crystals (EIC)

Bloch's theorem and the central equation
Electronic bandstructure and bandgaps

Metals, insulators, and semiconductors (MIS)

Electrons, holes and their effective masses in crystals
Chemical potential and insulating and metallic behaviour; activated conductivity
Intrinsic and extrinsic semiconductors
P-N junctions and semiconductor devices

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	Competence (1,2,3,4,5,6) Communication (1,2)	50%	Individual	Point-based marking (not rubric-based)
2. CA1: Term Test 1	Content in Part 1	Competence (1,2,3,4,5,6) Communication (1,2)	12.5%	Individual	Point-based marking (not rubric-based)
3. CA2: Term Test 2	Content in Part 2	Competence (1,2,3,4,5,6) Communication (1,2)	12.5%	Individual	Point-based marking (not rubric-based)
4. Homework problem sets	All	Competence (1,2,3,4,5,6) Creativity (1,2) Communication (1,2,3) Character (3)	25%	Team work; individual submission	Point-based marking (not rubric-based)
Total			100%		

Formative feedback
You will receive formative feedback through discussion within tutorial lessons.

Feedback is also given after each term test on the common mistakes and level of difficulty of the problems. Past exam questions and examiner's report are also made available to you.

Learning and Teaching approach

Approach	How does this approach support students in achieving the learning outcomes?
Lectures	Lectures will explain and emphasize the key concepts of Condensed Matter Physics. In so doing, during the lecture where concepts are introduced, there will also be series of warm-up questions, examples, as well as worked-out solutions to show how the concepts in the lectures are applied.
Tutorial	The students review main concepts learned in lectures with TAs. This helps them to digest and understand better.
Homework	The homework comprises questions that will help to develop understanding of the concepts of Condensed Matter Physics and will help to develop problem solving skills.

Reading and References

1. Introduction to Solid State Physics (8th Ed.) by Charles Kittel, Wiley (2004) – reference ISBN 978-0471415268
2. Solid State Physics (1st Ed.) by N. W. Ashcroft and N. D. Mermin, Cengage Learning (1976) – advanced reference ISBN 978-0030839931/ 0030839939 (College Ed.)
3. The Oxford Solid State Basics by Steven H. Simon, Oxford University Press (2017) – reference ISBN 978-0199680771

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-terms.
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-terms.

* 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
Assoc. Prof. Pinaki Sengupta	SPMS-PAP-05-03	+65 6592 1801	psengupta@ntu.edu.sg
Asst. Prof. Justin Song	SPMS-PAP-0407	+65 65137411	justinsong@ntu.edu.sg

Planned Weekly Schedule

Week	Topic	Course LO	Readings/ Activities
1	Course introduction and Crystal Structure	CSXRD 1	Lectures, Tutorials
2	Crystal Structure	CSXRD 2	Lectures, Tutorials
3	X-ray Diffraction	CSXRD 3, 4	Lectures, Tutorials
4	Lattice Vibrations and Phonons	LVP 5	Lectures, Tutorials
5	Lattice Vibrations and Phonons	LVP 6 +LVP 7	Lectures, Tutorials
6	Specific Heat of Solids	SHS 8	Lectures, Tutorials
7	Specific Heat of Solids	SHS 9	Lectures, Tutorials
8	Free Electron Theory	FET 10, 11	Lectures, Tutorials
9	Electrons in Crystals	EIC 12	Lectures, Tutorials
10	Electrons in Crystals	EIC 13	Lectures, Tutorials
11	Metals, Insulators, and Semiconductors	MIS 14, 15	Lectures, Tutorials
12	Metals, Insulators, and Semiconductors	MIS 16	Lectures, Tutorials
13	Metals, Insulators, and Semiconductors	MIS 17	Lectures, Tutorials

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 and PHMA 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;
		[PHMA 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.