PH4039 – Introduction to Condensed Matter Physics

Credits:	15.0	**Semester:**	1
Number of Lectures:	27	**Lecturer:**	Dr Chris Hooley
Academic Year:	2017-18		

Overview

This module explores how the various thermal and electrical properties of solids are related to the nature and arrangement of their constituent atoms. For simplicity, emphasis is given to crystalline solids. The module covers: the quantum-mechanical description of electron motion in crystals; the origin of band gaps and insulating behaviour; the reciprocal lattice and the Brillouin zone, and their relationships to X-ray scattering measurements; the band structures and Fermi surfaces of simple tight-binding models; the Einstein and Debye models of phonons, and their thermodynamic properties; low-temperature transport properties of insulators and metals, including the Drude model; the physics of semiconductors, including doping and gating; the effect of electron-electron interactions, including a qualitative account of Mott insulators; examples of the fundamental theory applied to typical solids.

Aims & Objectives

To set up a quantum-mechanical theory of the propagation of electrons and lattice vibrations in solids, and to link this theory to various observable properties (specific heat capacity, magnetic susceptibility, X-ray diffraction, electrical resistivity). To understand, using this theory, the following models and properties of solids:

- The Sommerfeld model of free and independent electrons, and its relation to the specific heat capacity of metals.
- The tight-binding model: band structures, Fermi surfaces, and band gaps. The notion of a band insulator.
- The nearly-free-electron model: the Fourier transform of the real-space potential, what it means, and its effect on the propagation of electron waves.
- The reciprocal lattice, and its explicit form for several simple types of real-space lattice.
- Lattice vibrations: their dispersion relation, and their quantisation as phonons.
- Electrical transport in solids: the Drude model, Umklapp processes, and the influence of disorder.
- The basic physics of semiconductors, including doping and gating.
- The effects of electron-electron interactions, including the Mott metal-insulator transition.

Learning Outcomes

By the end of this course, students should:

- be familiar with the magnitude and the temperature-dependence of common experimental observables in solids: specific heat capacity; magnetic susceptibility, electrical resistivity.
- be able to account for these using the Sommerfeld and Drude models.
- understand the meaning of the Fourier transform of a periodic potential, and be able to use it to calculate Laue diffraction patterns for simple real-space lattices.
- understand the physical significance of the Fermi surface, and calculate its shape for various filling factors and various real-space lattice geometries.
- understand how to determine the energy spectrum of the phonon modes of a solid, and the meaning of the Debye temperature.
- understand the importance of Umklapp processes in giving rise to electrical resistance, and be able to give an account of the influence of disorder on the resistivity of metals and insulators.
- understand the effects of doping and gating on simple semiconductors.
- understand the basic physics of electron-electron interactions in metals, including screening effects and the Mott metal-insulator transition.

Synopsis

Introductory material (3 lectures):

The quantum mechanics you'll need; the thermal and statistical physics you'll need; a survey of the properties of solids.

The Sommerfeld model – neutral fermions in a box (3 lectures):
Momentum space and the Fermi sphere; the density of states and the Fermi energy; the specific heat capacity and magnetic susceptibility of the Fermi gas.

The tight-binding model – neutral fermions hopping on a lattice (4 lectures):
Exact solution of the one-dimensional case; the interpretation of the phase ϕ; the Brillouin zone; the group velocity; Bloch oscillations; how a two-site basis leads to two energy bands.

The nearly-free-electron model – neutral fermions in a weak periodic potential (3 lectures):
The Fourier transform of a periodic potential; resonant scattering, standing waves, and band gaps; the Brillouin zone (again); multiple bands, and the comparison to the tight-binding model.

The reciprocal lattice (4 lectures):
The reciprocal lattice as the Fourier transform of a periodic potential; Laue diffraction; square vs. triangular Laue patterns; Fermi surfaces for tight-binding models with different lattice geometries.

Phonons – quantised vibrations of the crystal lattice (3 lectures):
An exact solution of a one-dimensional model of phonons; acoustic and optical phonons; the specific heat capacity of phonons; the Debye temperature.

Electrical transport in solids (3 lectures):
The Drude model; the temperature-dependence of the electrical resistivity of metals; insulators, metals, and semiconductors.

The physics of semiconductors (2 lectures):
Direct and indirect band gaps; doping and gating semiconductors.

Electron-electron interactions (2 lectures):
Screening of the Coulomb interaction in metals; the Mott metal-insulator transition.

Pre-requisites
PH2011, PH2012, MT2001 or (MT2501 and MT2503), (PH3081 or PH3082 or [MT2003 or (MT2506 and MT2507)]), PH3061 or CH3712

Anti-requisites
None

Assessment
Coursework = 20%, 2-hour Written Examination = 80%

Additional information on continuous assessment etc
The continuous assessment for the module consists of four tutorial sheets, each of which is worth 5 per cent of the credit for the module. Hand-out dates and hand-in deadlines for these may be found on the PH4039 Moodle page. Students taking this module will be divided into tutorial groups, each of which will meet four times during the semester.

Accreditation Matters
This module may not contain material that is part of the IOP “Core of Physics”, but does contribute to the wider and deeper learning expected in an accredited degree programme. The skills developed in this module, and others, contribute towards the requirements of the IOP “Graduate Skill Base”.

Recommended Books
Please view University online record: http://resourcelists.st-andrews.ac.uk/modules/ph4039.html

General Information
Please also read the general information in the School's honours handbook.