FINAL REMARKS (24 April 2013)

Solid State Physics is a vast subject. It is hard, if not impossible, to "teach" "all" of solid state physics. Because of this, textbooks and instructors typically choose between two approaches – either to go over many observed facts with qualitative discussions or to focus on a few basic topics. I chose the latter approach and focused on a few key concepts in solid state. These concepts include:

- Crystal structures – Bravais lattices and basis atoms.
- Binding in solids – cohesive energy, ionic crystals and Madelung constant (see Problem Sets).
- Wave propagation in solids (X-ray, wave of lattice vibration, electronic states (matter waves)) -- including the implications of having a periodic lattice and the importance of the reciprocal lattice, Fourier analysis of a periodic function, Brillouin zones and Wigner-Seitz cells
- Separation of lattice vibration problem and the electronic problem – Born-Oppenheimer approximation
- Lattice Vibrations -- derivation of dispersion relations, counting of normal modes and number of branches, the application of periodic boundary conditions to mimic an infinite solid, density of states, phonons and their contributions to heat capacity and thermal conductivity of solids
- Electronic states in solids – free electron model of metals, formation of energy bands, Bloch's theorem, Bloch function, electronic density of states, Fermi surface, approaches to band structures including expansion using plane waves, the empty lattice model, nearly free electron model and the opening of energy gap near Brillouin zone edges, the tight-binding model or LCAO approach.
- Electron Dynamics – equation of motion in the presence of an external force, velocity of electron in solid, acceleration and the reciprocal effective mass tensor, the effective mass.
- The above finishes the fundamental topics of solid state physics. Interesting effects are usually results of coupling them together, e.g. coupling electrons with phonons (or other ingredients such as impurities, size effect, etc.), electron-electron interaction, phonon-phonon interaction. Coupling with light (photons) has to do with the optical properties of solids (see Problem Sets for optical properties of metals).
- Basic semiconductor physics – materials, gaps, holes, electron and hole effective masses, mobility, Fermi energy and chemical potential in semiconductors, doping and impurity states, exciton.
- Transport Properties – response vs stimulations, Drude formula of the conductivity, Drude formula in ac regime (problem set), Drude formula in terms of density of states at

the Fermi energy, thermal conduction due to phonons and electrons, mean free paths and scattering time, scattering mechanisms lead to different temperature dependence in response, Hall effect (see problem set).

- Magnetic Properties – Physics behind treating atoms as tiny magnets, L, S, J, Hund's rules, Lande g-factor, Larmor diamagnetism, paramagnetism, Pauli susceptibility, Landau diamagnetism, and a bit about ferromagnetism.

The class notes, sample questions and the problem sets are designed to bring out these key concepts.

My idea is the following. If you understand the ideas behind wave propagation in periodic structure, lattice vibrations, electronic states, density of states, occupation probability functions, you should be able to learn the other topics in solid state physics by yourself.

There are a few topics that I didn't have time to cover in completeness, but can be picked up rather easily by an undergraduate. Some topics are covered in other physics courses. These include:

- Dielectric properties – you have learnt some of them in your EM courses (e.g. dielectric constants, see Chapter 4 of Griffiths' textbook), but there are many useful materials (piezoelectric, ferroelectric, high dielectric constant materials, etc.)
- Optical properties – a very important experimental probe on solids is to study their optical properties. You have learnt some of them in your EM courses (e.g. Lorentz oscillator model of dielectric constant, Snell's laws (reflection and transmission coefficients), reflection from metal – skin depth, plasma frequency, etc.- see Chapter 9 of Griffiths' textbook). Plasmonics is a very hot topic in research now. We did some optical properties in problem sets and in the chapter on semiconductors.
- Superconductivity – I chose to skip this topic because a reasonable understanding of the topic requires a many-electron approach. It needs a half-semester course to do justice to the topic. To celebrate 100 years of superconductivity,
- We also use graphene to illustrate some basic concepts. A talk on quasicrystals was given.

Here, I list some useful references at different levels that may be useful for your further studies on solid state physics.

1. *At a level equivalent to our course.*
    - J.R. Christman, "*Fundamentals of Solid State Physics*". We have covered about

310 pages of this 500-page book. This book is a good companion to Kittel's book in that it covers nearly the same topics, but taking away the many figures and data and explaining the physics in more detail.

- J.R. Hook and H.E. Hall, "*Solid State Physics*". A standard undergraduate text that separates the theoretical discussion into two parts – easier ones in early chapters and formal stuff at the end. We have covered nearly 300 pages of this 400-page book.
- The Chinese book "*Solid State Physics*" by K. Huang and others. Out of 13 chapters in this book, we have done a large part of the first eight chapters. [The book was written for a curriculum with over 70 teaching hours in a semester.]
- The book "*Elementary Solid State Physics: Principles and Applications*" by Omar is also useful. There are, unfortunately, many misprints in the book, but the physics is discussed clearly (in particular, the chapters on band theory).
- Solid state has to do with real stuffs and one needs to acquire a good sense to the numbers. The book by Michael de Podesta "*Understanding the Properties of Matter*" has two chapters on solids (the other chapters are on gases, liquids, and phase changes). The book provides many tables for materials data (some of which we used in our class notes).
- John P. McKelvey, "*Solid State Physics for engineers and materials science*". I found this book surprisingly clear. For students who want all the necessary quantum physics, thermodynamics and statistical physics printed out in a solid state textbook, this is the book.

2. *Going to the next level.*

- N.W. Ashcroft and N.D. Mermin, "*Solid State Physics*". A standard beginning graduate textbook on solid state physics. Using more quantum mechanics, but not much many-body approach. Many of the topics discussed in our course are treated at a similar level to this book. [I heard that there would be a new edition coming out, with a new coauthor doing the revision!]
- W. Harrison, "*Solid State Theory*". There is a Dover (inexpensive) edition. A good book to learn a more theoretical approach to solid states.
- R. Dalven, "*Introduction to Applied Solid State Physics*". This is an excellent book to learn the *applications* of solid state physics. It ties up nicely to Kittel's "Introduction to Solid State Physics" (thus our course), as it assumes such a background. The topics include: semiconductor device physics, EM radiation detectors, superconductive devices, magnetic materials and devices, nonlinear optical materials. The discussion is on physics, but tuned to an audience who are probably doing experiments. The chapters can be read in random order. Highly

recommended.

- J.J. Quinn and K.-S. Yi, "*Solid State Physics – Principles and Modern Applications*". This is a 2009 Springer book available as e-book. The book has two parts. We have done much of Part 1 (first 9 chapters). Part 2 (another 7 chapters) is more on many-body effects suitable for a beginning graduate-level course. Nicely written.
- W. Harrison, "*Applied Quantum Mechanics*". This is a book written for graduate students in materials science and electrical engineering. It is about quantum mechanics, but the author used the context of solid state physics to illustrate the techniques in quantum mechanics. A good undergraduate physics student can follow a large part of the book. There are very readable chapters on "Quantum Optics" and "Many-body effects".

3. *More "modern books"* – A few relatively new books are becoming standard graduate texts. Typically, these books include some many-body approaches to solid state and/or discussion on numerical methods.
   - For those who wants to know more about band-structure calculations, especially first-principle calculations: Richard M. Martin, "*Electronic Structure: Basic Theory and Practical Methods*". This has become the standard reference to learn how to do ab initio calculations. There are also free computer programs on the web for very serious band structure calculations. Note that computational materials science is a fashionable research area. It is available in low-price edition in Mainland.
   - For those who want to learn the language of advanced solid state physics, two books are recommended. M.P. Marder, "*Condensed Matter Physics*" (a well-thought and well-written book that covers nearly every topic, the author starts the discussion from an undergraduate level and brings it to an end at a beginning research level, like a dictionary). Philip W. Phillips. "*Advanced Solid State Physics*". This book has a good selection of modern topics that are of research interest, e.g., localization, Anderson model, Hubbard model, Kondo problem, etc. However, the discussion is presented in such a way that it needs some background (e.g. Green's functions), but the background is not covered in the text. It is a good place to get a rough idea on many fascinating topics, although one needs to read more from other sources in order to understanding the details. Another new book of the same kind is "*Basic Aspects of the Quantum Theory of Solids: Order and Elementary Excitations*" by Daniel Khomskii. It gives a rough idea of many new ideas in condensed matter physics.
   - For those who want to learn more about useful ideas in condensed matter physics (not so hard-core solid state, but about phase transitions, response functions, liquid crystals, etc.): P.M. Chaikin and T.C. Lubensky, "*Principles of Condensed Matter*

Physics". It was the first book on condensed matter physics by two excellent authors. This is a good companion to the more "philosophical" book by P.W. Anderson, "*Basic notions of condensed matter physics*".

4. A few nice introductions (not necessarily difficult) to *specialized topics*:
   - For those interested in optical properties, two books are recommended. F. Wooten, "*Optical Properties of Solids*" (a more theoretical inclined book). M. Fox, "*Optical Properties of Solids*" (a balanced book on theory and experiments that can be understood by an undergraduate – it is written for the British MPhys degree, so it is very close to our final year BSc courses). Fox also has a book on "*Quantum Optics: An Introduction*", which is very readable.
   - For those interested in magnetic properties, two books are recommended. Stephen Blundell, "*Magnetism in Condensed Matter*" (an excellent book that takes students from undergraduate level to beginning research level). Daniel Mattis, "*Theory of Magnetism*" (this is an old book, but the author published another book entitled "*The Theory of Magnetism Made Simple*" recently). Magnetism in solids is a forever growing research field.
   - For those interested in Superconductivity, I would recommend "*Superconductivity*" by J.B. Ketterson and S.N. Song.

5. For those who want to learn the *formal many-body approach to solid state physics*:
   - E.N. Economou, "*Green's functions in Quantum Physics*" (actually the book is more on one-particle approach, but it is a nice introduction to the idea behind using Green's function).
   - Gerald Mahan, "*Many-particle physics*" (still the best 1000-page book that covers the detail of many calculations in many-body theory of solid state physics, using the language of Green's functions).
   - S. Doniach and E.H. Sondheimer, "*Green's functions for solid state physicists*" (a shorter introduction than Mahan and based on the equation of motion approach, which may be easier to follow, in evaluating Greens' function.)
   - N. Nagaosa, "*Quantum field theory in strongly correlated electronic system*" (the author explained everything in great detail and used more path integral approach than the Green's functions).

6. *Reading solid state physics for enjoyment.* Some day, you may want to read something simple or to pick up some solid state physics again quickly (your job may need it) without going through the details. For this purpose, I would recommend
   - Michael de Podesta, "*Understanding the Properties of Matter*" (Year 1 physics is

sufficient to follow the book)

- Richard Turton, “*The Physics of Solids*” (physics discussed in words and supplemented by a few key equations)
- J.D. Livingston, “*Electronic Properties of Engineering Materials*” (an excellent book on real solid state physics using an user-friendly approach)
- M. Riordan and L. Hoddeson, “*Crystal Fire*” (a popular science book on the story behind the invention of the transistor)
- L. Hoddeson and V. Daitch, “*True Genius: The life and science of John Bardeen*” (a popular science book on the only physicist who won 2 Nobel Physics Prizes, one for his invention of the transistor and another for his theory of superconductivity)
- B.S. Chandrasekhar, “*Why things are the way they are*” (a good attempt on giving a popular account on properties of materials)

To follow latest developments in condensed matter physics and other branches of physics, we can register free-of-charge into:

- physicsworld.com [run by Institute of Physics, UK]
- physics.aps.org [run by American Physical Society]
- Science
- Nature

These places will send you weekly highlights on what is happening in physics and in science.

And this ends our PHYS4450 Solid State Physics course.

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