Condensed Matter Physics

Second Edition

Michael P. Marder

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Preface

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Using this book.

This textbook provides material for a one-year graduate course on condensed matter physics. It contains introductions to classic subjects, and it also presents topics I believe will continue to occupy the field in the future. The book teaches not only about the effective masses of electrons in semiconductor crystals and band theory, but also about quasicrystals, dynamics of phase separation, why rubber is more floppy than steel, electron interference in nanometer-sized channels, and the quantum Hall effect.

It is arranged in six parts, convenient for dividing into two semesters or three quarters. However, there is more material than can reasonably be covered in one year. My experience suggests that an instructor should aim to cover roughly two-thirds of the material in each part. The remainder is available for reference. Every instructor will find that some of the topics are very elementary and others are quite advanced. However, instructors with different backgrounds will disagree to a surprising extent on which are which. The web site associated with the book, `http://chaos.ph.utexas.edu/~cmp`, contains sample syllabi, as well as corrections, and other information.

Each chapter is followed by a collection of problems. Some are brief derivations, but many introduce new topics and are fairly lengthy. An instructor's manual is available to aid in decisions on what to assign. Whether in academic or industrial posts, experimentalists and theorists must all become fluent in manipulating data and symbols with the computer. Therefore, many of the problems involve numerical work, ranging from no more than plotting graphs to a series of linked exercises that produces a simple band structure code.

The book presumes a working knowledge of quantum mechanics, statistical mechanics, and electricity and magnetism. I decided to exclude many-body Green functions, which become such an absorbing formal world of their own that they too easily drive physical reasoning out of an introductory course. However, as the book proceeds I do begin to employ second quantization, and it becomes quite common by the time of the section on magnetism.

If simple arguments explain a phenomenon, I present them, but I also have paid some attention to the actual historical process by which ideas were accepted, and I try to explain in detail some of the calculations and experimental data that actually convinced the specialists. Not all the subjects discussed in this book are closed; even simple questions do not always have answers; and theory and experiment do not always completely agree. The topics that can today be presented only within a distressing cloud of uncertainty are precisely the ones most likely to remain central to the development of condensed matter physics.

References to original literature. There are two attitudes toward references to original literature. One is that it is ridiculous to "cite the original work of Maxwell, for example, which nobody bothers to look up anyway" [Aharoni (1996), p. vii].

Maxwell himself disagreed. He believed that it "is of great advantage to the student of any subject to read the original memoirs on that subject, for science is always most completely assimilated when it is found in its nascent state" [Maxwell (1904), p. xi]. While it would be impossible to cite all papers responsible for the development of condensed matter physics without having reference lists longer than the remainder of the book, I have cited some of the most influential papers for two reasons. First, anyone who is part of research today knows how strongly all authors feel about having contributions recognized, and it hardly seems fair to have older generations drift entirely out of consciousness simply because they are no longer around to defend themselves. Second, original papers on difficult topics sometimes provide clearer explanations than anything that ever follows. Review articles quickly race over elementary points so as to provide comprehensive coverage of current developments, while textbooks easily make assertions, ignoring the complex web of evidence that eventually produced a consensus.

To try to ensure that major portions of the field were not left unrepresented, I somewhat arbitrarily chose three series of review articles and included a reference to almost every article with a bearing on condensed matter physics in the last 30 years. These are: *Solid State Physics: Advances in Research and Applications*, *Reviews of Modern Physics*, and *Physics Today*. Some of these articles have a very narrow focus, but the degree of difficulty can happily be estimated with little effort by using Ziman's "*coefficient of non-specificity*, calculated as follows: transform the title into a succession of A adjectives qualifying S substantives, omitting redundant words like 'physics', 'effects', 'properties', 'materials', etc. Then take the ratio A/S. Inspection ... shows quite clearly that if the coefficient is greater than 3 the article is too specialized.... The optimum seems to be in the range $1 \leq A/S \leq 2$" [Ziman (1961)].

Origin of the field. The discovery of quantum mechanics raised the hope of explaining the familiar world from equations at the atomic scale. In early stages this enterprise was largely restricted to metals in crystalline form. The field began as "metals physics," but the term excluded widely studied solids such as ionic crystals. "Solid state physics" was adopted instead, with creation of the Division of Solid State Physics by the American Physical Society in 1947. A decade later even "solid state" was becoming too restrictive for a field tackling liquid metals, liquid helium, liquid crystals, and polymer melts. In 1963, Busch began editing a journal called *Physik der Kondensierten Materie/Physique de la matière condensée/Physics of condensed matter*. The daring term gained usage slowly. The American Physical Society Division of Solid State Physics voted in April 1978 to change its name to the Division of Condensed Matter Physics.

Having set itself the modest goal of explaining the whole material world, including structural and electronic properties of solids and liquids, the field of condensed matter physics has become enormous. It overlaps statistical physics, materials physics, and fluid and solid mechanics. The diversity in topics obscures a unity of approach.

Experiments play a crucial role. The systems studied by condensed matter physics are far too complicated for anyone to deduce their qualitative behavior from atomic scale considerations. Only once experience has determined the nature of the qualitative problem does theory have a chance of explaining it. On the other hand, most experiments are impossible to interpret quantitatively without theoretical support.

Condensed matter theories search for relations between separate levels of description. The fundamental underlying equations are largely useless, so theories of condensed matter are largely based upon equations whose form is guessed rather than derived, and in which parameters or methods of approximation are constrained by symmetry and determined by experiment. Often there is a friendly competition between simple models, employed for conceptual understanding, and attempts at realistic computation. There is sometimes a tendency to speak a bit contemptuously of the simple models. However, "for many purposes a theory whose consequences are easily followed is preferable to one which is more fundamental but also more unwieldy" [Thomson (1907), p. 2].

Acknowledgements. In the course of preparing this manuscript, I received generous assistance from dozens of people who supplied figures, answered queries, and took the time to debunk anecdotes that not only seemed to good to be true, but were in fact too good to be true. Some who wrote comments include Martin Bazant, Hans Bethe, Danita Boonchaisri, Steve Girvin, Stefan Hüfner, David Lazarus, Neil Mathur, David Mermin, George Sawatzky, and John Ziman. Lynn Boatner, Janie Gardner, and Douglas Corrigan of Oak Ridge National Laboratory contributed the micrograph appearing on the front cover. At The University of Texas at Austin, I was particularly helped by Alex de Lozanne, John Markert, Jim Erskine, Ken Shih, and Hugo Steinfink. Bob Martinez was the first person after me to try teaching from the text. Ted Einstein of the University of Maryland, Sokrates Pantelides of Vanderbilt University, and Rashmi Desai of The University of Toronto have also taught from draft versions, and they found embarrassing errors that I am perfectly glad to see disappear with the drafts. Roberto Diener trapped many additional errors. Caryn Cluiss assisted in the task of organizing permissions from numerous publishers.

As part of writing the book, I wanted to learn about band structure calculations. My colleague Len Kleinman helped with a steady supply of physical insight, provocative commentary, and warnings about the *method of successful approximations*, where twiddling hidden parameters stops as soon as one obtains an expected answer. Hans Skriver kindly supplied me with a copy of the code described in Skriver (1984). Roland Stumpf supplied improved versions of the plane-wave pseudopotential code described in Stumpf and Scheffler (1994), and he also answered interminable series of questions. Most recently, calculations were performed using `VASP` (Vienna ab-initio simulation program) developed at the Institut für Theoretische Physik of the Technische Universität Wien by Kresse and Hafner (1993), Kresse and Hafner (1994), Kresse and Furthmüller (1996b), and Kresse and Furthmüller (1996a).

I owe special thanks to Qian Niu. On many occasions I found myself baffled

by an apparently simple point, and I asked one expert after another without finding a resolution. When all other avenues failed, I took the stairs one flight down to Qian's office, where after a brief smile he explained matters to me with perfect clarity.

The Exxon Education Foundation and the National Science Foundation gave me the means to buy a laptop computer, which in turn allowed me to continue thinking about condensed metaphysics in unexpected places. My thanks to the citizens of Gavdos for allowing me to use cast-off solar panels, to Elias Kyriakopoulos for repairing a 12-volt power inverter when all seemed hopeless, and to Nikos Papanicolaou for unquestioning hospitality at the University of Crete whenever life without a library became just too difficult. Last thanks of all to my wife Elpida, without whose quiet encouragement and example of determination I would never have had the courage to complete this book.

Austin, Texas
September, 1999

MICHAEL MARDER

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Preface to second edition

The goal of this second edition is to consolidate thousands of changes suggested by readers since the first was published, to improve presentation of several topics, and to add a small number of new ones.

Minor typographical errors were originally very numerous, and over 40 individuals from all over the world contributed corrections. The top 5 error-finders found so many that they deserve special recognition: Roberto Diener read the book cover to cover, checked every derivation, and found 244; Dominic Holland found 33; Erkki Thuneberg found 20; Dale Kitchen found 15; Qian Niu found 11. Particularly extensive and detailed comments arrived from Wesley Matthews, Sasha Chernyshev, and Vincenzo Fiorentini.

The primary reason for many students to learn Condensed Matter Physics is for the topics of electron and phonon band structures. The presentation of these topics had been rushed, and the new presentation is slower, working out one-dimensional examples before proceeding to the full three-dimensional and abstract formulations.

The entire discipline of condensed matter is roughly ten percent older than when the first edition was written, so adding some new topics seemed appropriate. For the most part, these new topics were ones whose importance is increasingly appreciated, rather than material first derived in the last few years. They include graphene and nanotubes, Berry phases, Luttinger liquids, diffusion, dynamic light scattering, and spin torques.

The world in which this edition was produced is slightly different from that of the previous one. The first edition required many, many days walking up and down library stacks searching for articles. Now almost all academic publications are available through the internet in the world's most remote corners. Laptop computers were a rare luxury twelve years ago. Now they are a common commodity. The discipline of condensed matter physics itself underlies these technical advances. The benefits of instant connection everywhere to everything are partly offset by the corresponding demand to respond instantly to everyone everywhere about everything. I thank the National Science Foundation for sustained support that allowed me some periods of peace where I could finish this book.

Phalasarna, Crete MICHAEL MARDER
June, 2010

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Cover, Upper Image: Zinc oxide (ZnO) is a wide band gap semiconductor with a multitude of applications in the areas of microelectronic devices, catalysis, varistors, light-emitting diodes, gas sensing, and scintillators. ZnO is a hexagonal, wurtzite-structure material that is characterized by polar Zn-terminated and O-terminated surfaces. In the top micrograph, chemical reactions produced by a high-temperature treatment in zinc metal vapor have produced morphological changes on the surface of a ZnO single crystal. Optical interference contrast microscopy reveals the hexagonal-symmetry ZnO surface topology in the form of color variations. Micrograph by: L. A. Boatner and Hu Longmire, Materials Science and Technology Division, Oak Ridge National Laboratory **Bottom Image:** Transition metal carbides are characterized by high melting points, high hardness, high-temperature corrosion resistance, and an ability to maintain their strength at elevated temperatures. The optical interference contrast micrograph shown at the bottom of the cover illustrates the morphological features of a fracture surface on a single crystal of titanium carbide. This material is brittle and is prone to fracture at room temperature, but it can be used as a structural material at high temperatures where the brittleness is reduced. Micrograph by: L. A. Boatner and Hu Longmire, Materials Science and Technology Division, Oak Ridge National Laboratory

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