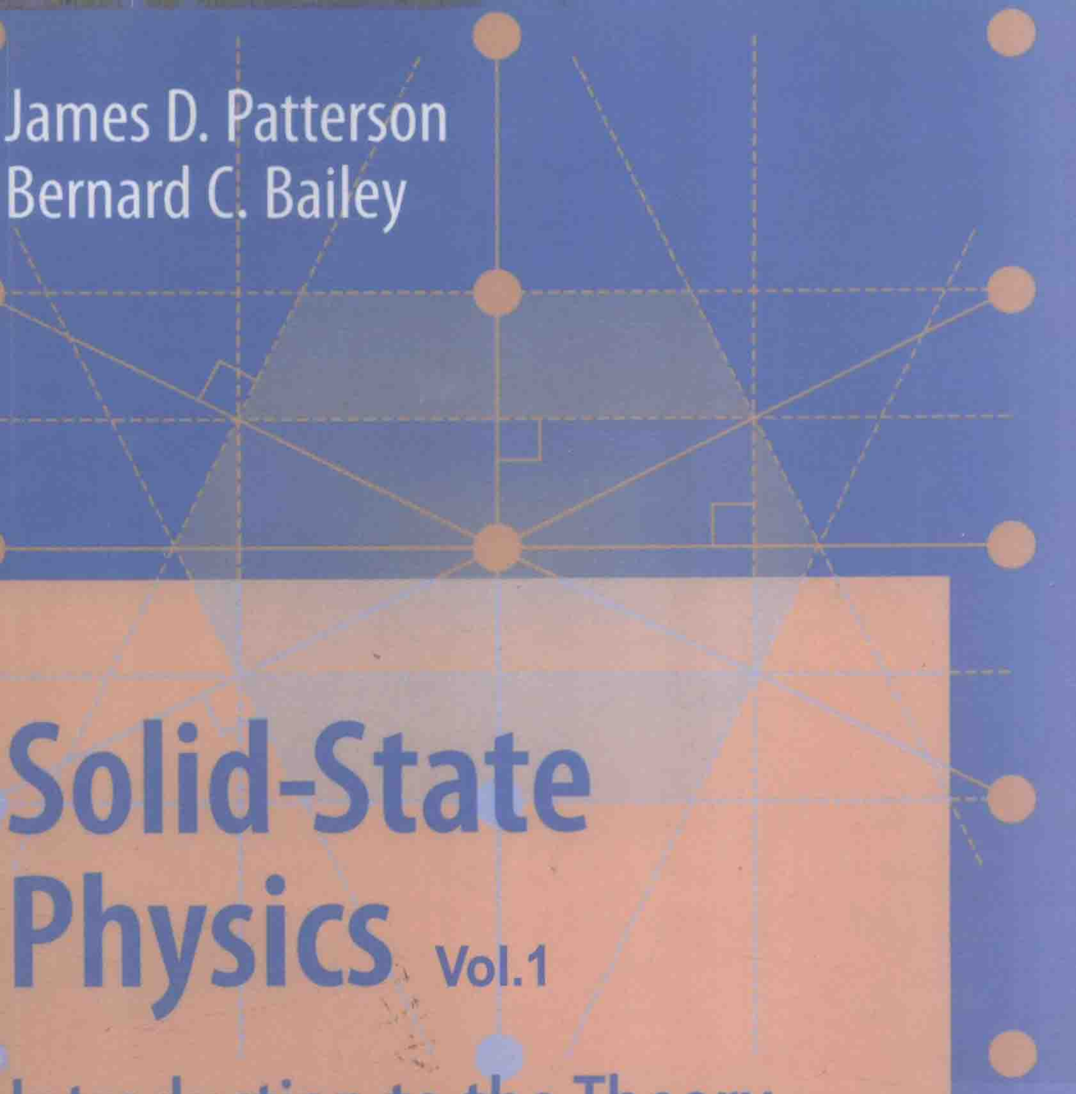

James D. Patterson
Bernard C. Bailey

# Solid-State Physics Vol.1

## Introduction to the Theory

## 固态物理学 第1卷

Springer

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With 202 Figures

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# Preface

Learning solid-state physics requires a certain degree of maturity, since it involves tying together diverse concepts from many areas of physics. The objective is to understand, in a basic way, how solid materials behave. To do this one needs both a good physical and mathematical background. One definition of solid-state physics is that it is the study of the physical (e.g. the electrical, dielectric, magnetic, elastic, and thermal) properties of solids in terms of basic physical laws. In one sense, solid-state physics is more like chemistry than some other branches of physics because it focuses on common properties of large classes of materials. It is typical that solid-state physics emphasizes how physical properties link to the electronic structure. In this book we will emphasize crystalline solids (which are periodic 3D arrays of atoms).

We have retained the term solid-state physics, even though condensed-matter physics is more commonly used. Condensed-matter physics includes liquids and non -crystalline solids such as glass, about which we have little to say. We have also included only a little material concerning soft condensed matter (which includes polymers, membranes and liquid crystals – it also includes wood and gelatins).

Modern solid-state physics came of age in the late 1930s and early 1940s (see Seitz [82]), and had its most extensive expansion with the development of the transistor, integrated circuits, and microelectronics. Most of microelectronics, however, is limited to the properties of inhomogeneously doped semiconductors. Solid-state physics includes many other areas of course; among the largest of these are ferromagnetic materials, and superconductors. Just a little less than half of all working physicists are engaged in condensed matter work, including solid-state.

One earlier version of this book was first published 30 years ago (J.D. Patterson, *Introduction to the Theory of Solid State Physics*, Addison-Wesley Publishing Company, Reading, Massachusetts, 1971, copyright reassigned to JDP 13 December, 1977), and bringing out a new modernized and expanded version has been a prodigious task. Sticking to the original idea of presenting basics has meant that the early parts are relatively unchanged (although they contain new and reworked material), dealing as they do with structure (Chap. 1), phonons (2), electrons (3), and interactions (4). Of course, the scope of solid-state physics has greatly expanded during the past 30 years. Consequently, separate chapters are now devoted to metals and the Fermi surface (5), semiconductors (6), magnetism (7, expanded and reorganized), superconductors (8), dielectrics and ferroelectrics (9), optical properties (10), defects (11), and a final chapter (12) that includes surfaces, and brief mention of modern topics (nanostructures, the quantum Hall effect, carbon nanotubes, amorphous materials, and soft condensed matter). The reference list has been brought up to date, and several relevant topics are further discussed in the appendices. The table of contents can be consulted for a full list of what is now included.

The fact that one of us (JDP) has taught solid-state physics over the course of this 30 years has helped define the scope of this book, which is intended as a textbook. Like golf, teaching is a humbling experience. One finds not only that the students don't understand as much as one hopes, but one constantly discovers limits to his own understanding. We hope this book will help students to begin a life-long learning experience, for only in that way can they gain a deep understanding of solid-state physics.

Discoveries continue in solid-state physics. Some of the more obvious ones during the last thirty years are: quasicrystals, the quantum Hall effect (both integer and fractional – where one must finally confront new aspects of electron–electron interactions), high-temperature superconductivity, and heavy fermions. We have included these, at least to some extent, as well as several others. New experimental techniques, such as scanning probe microscopy, LEED, and EXAFS, among others have revolutionized the study of solids. Since this is an introductory book on solid-state theory, we have only included brief summaries of these techniques. New ways of growing crystals and new "designer" materials on the nanophysics scale (superlattices, quantum dots, etc.) have also kept solid-state physics vibrant, and we have introduced these topics. There have also been numerous areas in which applications have played a driving role. These include semiconductor technology, spin-polarized tunneling, and giant magnetoresistance (GMR). We have at least briefly discussed these as well as other topics.

Greatly increased computing power has allowed many ab initio methods of calculations to become practical. Most of these require specialized discussions beyond the scope of this book. However, we continue to discuss pseudopotentials, and have added a Section on density functional techniques.

Problems are given at the end of each chapter (many new problems have been added). Occasionally they are quite long and have different approximate solutions. This may be frustrating, but it appears to be necessary to work problems in solid-state physics in order to gain a physical feeling for the subject. In this respect, solid-state physics is no different from many other branches of physics.

We should discuss what level of students for which this book is intended. One could perhaps more appropriately ask what degree of maturity of the students is assumed? Obviously, some introduction to quantum mechanics, solid-state physics, thermodynamics, statistical mechanics, mathematical physics, as well as basic mechanics and electrodynamics is necessary. In our experience, this is most commonly encountered in graduate students, although certain mature undergraduates will be able to handle much of the material in this book.

Although it is well to briefly mention a wide variety of topics, so that students will not be "blind sided" later, and we have done this in places, in general it is better to understand one topic relatively completely, than to scan over several. We caution professors to be realistic as to what their students can really grasp. If the students have a good start, they have their whole careers to fill in the details.

The method of presentation of the topics draws heavily on many other solid-state books listed in the bibliography. Acknowledgment due the authors of these books is made here. The selection of topics was also influenced by discussion with colleagues and former teachers, some of whom are mentioned later.

We think that solid-state physics abundantly proves that more is different, as has been attributed to P. W. Anderson. There really are emergent properties at higher levels of complexity. Seeking them, including applications, is what keeps solid-state physics alive.

In this day and age, no one book can hope to cover all of solid-state physics. We would like to particularly single out the following books for reference and or further study. Terms in brackets refer to references listed in the Bibliography.

1. Kittel – 7th edition – remains unsurpassed for what it does [23, 1996]. Also Kittel's book on advanced solid-state physics [60, 1963] is very good.

2. Ashcroft and Mermin, *Solid State Physics* – has some of the best explanations of many topics I have found anywhere [21, 1976].

3. Jones and March – a comprehensive two-volume work [22, 1973].

4. J.M. Ziman – many extremely clear physical explanation [25, 1972], see also Ziman's classic *Electrons and Phonons* [99, 1960].

5. O. Madelung, *Introduction to Solid-State Theory* – Complete with a very transparent and physical presentation [4.25].

6. M.P. Marder, *Condensed Matter Physics* – A modern presentation, including modern density functional methods with references [3.29].

7. P. Phillips, *Advanced Solid State Physics* – A modern Frontiers in Physics book, bearing the imprimatur of David Pines [A.20].

8. Dalven – a good start on applied solid-state physics [32, 1990].

9. Also Oxford University Press has recently put out a "Master Series in Condensed Matter Physics." There are six books which we recommend.
   a) Martin T. Dove, *Structure and Dynamics* – An atomic view of Materials [2.14].
   b) John Singleton, *Band Theory and Electronic Properties of Solids* [3.46].
   c) Mark Fox, *Optical Properties of Solids* [10.12].
   d) Stephen Blundell, *Magnetism in Condensed Matter* [7.9].
   e) James F. Annett, *Superconductivity, Superfluids, and Condensates* [8.3].
   f) Richard A. L. Jones, *Soft Condensed Matter* [12.30].

A word about notation is in order. We have mostly used SI units (although gaussian is occasionally used when convenient); thus $\boldsymbol{E}$ is the electric field, $\boldsymbol{D}$ is the electric displacement vector, $\boldsymbol{P}$ is the polarization vector, $\boldsymbol{H}$ is the magnetic field, $\boldsymbol{B}$ is the magnetic induction, and $\boldsymbol{M}$ is the magnetization. Note that the above quantities are in boldface. The boldface notation is used to indicate a vector. The magnitude of a vector $\mathbf{V}$ is denoted by $V$. In the SI system $\mu$ is the permeability ($\mu$ also represents other quantities). $\mu_0$ is the permeability of free space, $\varepsilon$ is the permittivity, and $\varepsilon_0$ the permittivity of free space. In this notation $\mu_0$ should not be confused with $\mu_B$, which is the Bohr magneton [$= |e|\, \hbar/2m$, where $e$ = magnitude of electronic charge (i.e. $e$ means $+|e|$ unless otherwise noted), $\hbar$ = Planck's constant divided by $2\pi$, and $m$ = electronic mass]. We generally prefer to write $\int A \mathrm{d}^3 r$ or $\int A \mathrm{d}\mathbf{r}$ instead of $\int A\, \mathrm{d}x\, \mathrm{d}y\, \mathrm{d}z$, but they all mean the same thing. Both $\langle i|H|j\rangle$ and $(i|H|j)$ are used for the matrix elements of an operator $H$. Both mean $\int \psi^* H \psi \mathrm{d}\tau$ where the integral over $\tau$ means to integrate over whatever space is appropriate (e.g., it could mean an integral over real space and a sum over spin space). By $\sum$ a summation is indicated and by $\prod$ a product. The Kronecker delta $\delta_{ij}$ is 1 when $i = j$ and zero when $i \neq j$. We have not used covariant and contravariant spaces; thus $\delta_{ij}$ and $\delta_i^j$, for example, mean the same thing. We have labeled sections by A for advanced, B for basic, and EE for material that might be especially interesting for electrical engineers, and similarly MS for materials science, and MET for metallurgy. Also by [number], we refer to a reference at the end of the book.

There are too many colleagues to thank, to include a complete list. JDP wishes to specifically thank several. A beautifully prepared solid-state course by Professor W. R Wright at the University of Kansas gave him his first exposure to a logical presentation of solid-state physics, while also at Kansas, Dr. R.J. Friauf, was very helpful in introducing JDP to the solid-state. Discussions with Dr. R.D. Redin, Dr. R.G. Morris, Dr. D.C. Hopkins, Dr. J. Weyland, Dr. R.C. Weger and others who were at the South Dakota School of Mines and Technology were always useful. Sabbaticals were spent at Notre Dame and the University of Nebraska, where working with Dr. G.L. Jones (Notre Dame) and D.J. Sellmyer (Nebraska) deepened JDP's understanding. At the Florida Institute of Technology, Drs. J. Burns, and J. Mantovani have read parts of this book, and discussions with Dr. R. Raffaelle and Dr. J. Blatt were useful. Over the course of JDP's career, a variety of summer jobs were held that bore on solid-state physics; these included positions at Hughes Semiconductor Laboratory, North American Science Center, Argonne National Laboratory, Ames Laboratory of Iowa State University, the Federal University of Pernambuco in Recife, Brazil, Sandia National Laboratory, and the Marshal Space Flight Center. Dr. P. Richards of Sandia, and Dr. S.L. Lehoczky of Marshall, were particularly helpful to JDP. Brief, but very pithy conversations of JDP with Dr. M. L. Cohen of the University of Califonia/ Berkeley, over the years, have also been uncommonly useful.

Dr. B.C. Bailey would like particularly to thank Drs. J. Burns and J. Blatt for the many years of academic preparation, mentorship, and care they provided at Florida Institute of Technology. A special thanks to Dr. J.D. Patterson who, while Physics Department Head at Florida Institute of Technology, made a conscious decision to take on a coauthor for this extraordinary project.

All mistakes, misconceptions and failures to communicate ideas are our own. No doubt some sign errors, misprints, incorrect shading of meanings, and perhaps more serious errors have crept in, but hopefully their frequency decreases with their gravity.

Most of the figures, for the first version of this book, were prepared in preliminary form by Mr. R.F. Thomas. However, for this book, the figures are either new or reworked by the coauthor (BCB).

We gratefully acknowledge the cooperation and kind support of Dr. C. Asheron, Ms. E. Sauer, and Ms. A. Duhm of Springer. Finally, and most importantly, JDP would like to note that without the constant encouragement and patience of his wife Marluce, this book would never have been completed.

*J.D. Patterson, Rapid City, South Dakota*
*October 2005* *B.C. Bailey, Cape Canaveral, Florida*

# Contents

# 7 Magnetism, Magnons, and Magnetic Resonance

The first chapter was devoted to the solid-state medium (i.e. its crystal structure and binding). The next two chapters concerned the two most important types of energy excitations in a solid (the electronic excitations and the phonons). *Magnons* are another important type of energy excitation and they occur in magnetically ordered solids. However, it is not possible to discuss magnons without laying some groundwork for them by discussing the more elementary parts of magnetic phenomena. Also, there are many magnetic properties that cannot be discussed by using the concept of magnons. In fact, the study of magnetism is probably the first solid-state property that was seriously studied, relating as it does to lodestone and compass needles.

Nearly all the magnetic effects in solids arise from electronic phenomena, and so it might be thought that we have already covered at least the fundamental principles of magnetism. However, we have not yet discussed in detail the electron's spin degree of freedom, and it is this, as well as the orbital angular moment that together produce magnetic moments and thus are responsible for most magnetic effects in solids. When all is said and done, because of the richness of this subject, we will end up with a rather large chapter devoted to magnetism.

We will begin by briefly surveying some of the larger-scale phenomena associated with magnetism (diamagnetism, paramagnetism, ferromagnetism, and allied topics). These are of great technical importance. We will then show how to understand the origin of ordered magnetic structures from a quantum-mechanical viewpoint (in fact, strictly speaking this is the only way to understand it). This will lead to a discussion of the Heisenberg Hamiltonian, mean field theory, spin waves and magnons (the quanta of spin waves). We will also discuss the behavior of ordered magnetic systems near their critical temperature, which turns out also to be incredibly rich in ideas.

Following this we will discuss magnetic domains and related topics. This is of great practical importance.

Some of the simpler aspects of magnetic resonance will then be discussed as it not only has important applications, but magnetic resonance experiments provide direct measurements of the very small energy differences between magnetic sublevels in solids, and so they can be very sensitive probes into the inner details of magnetic solids.

We will end the chapter with some brief discussion of recent topics: the Kondo effect, spin glasses, magnetoelectronics, and solitons.