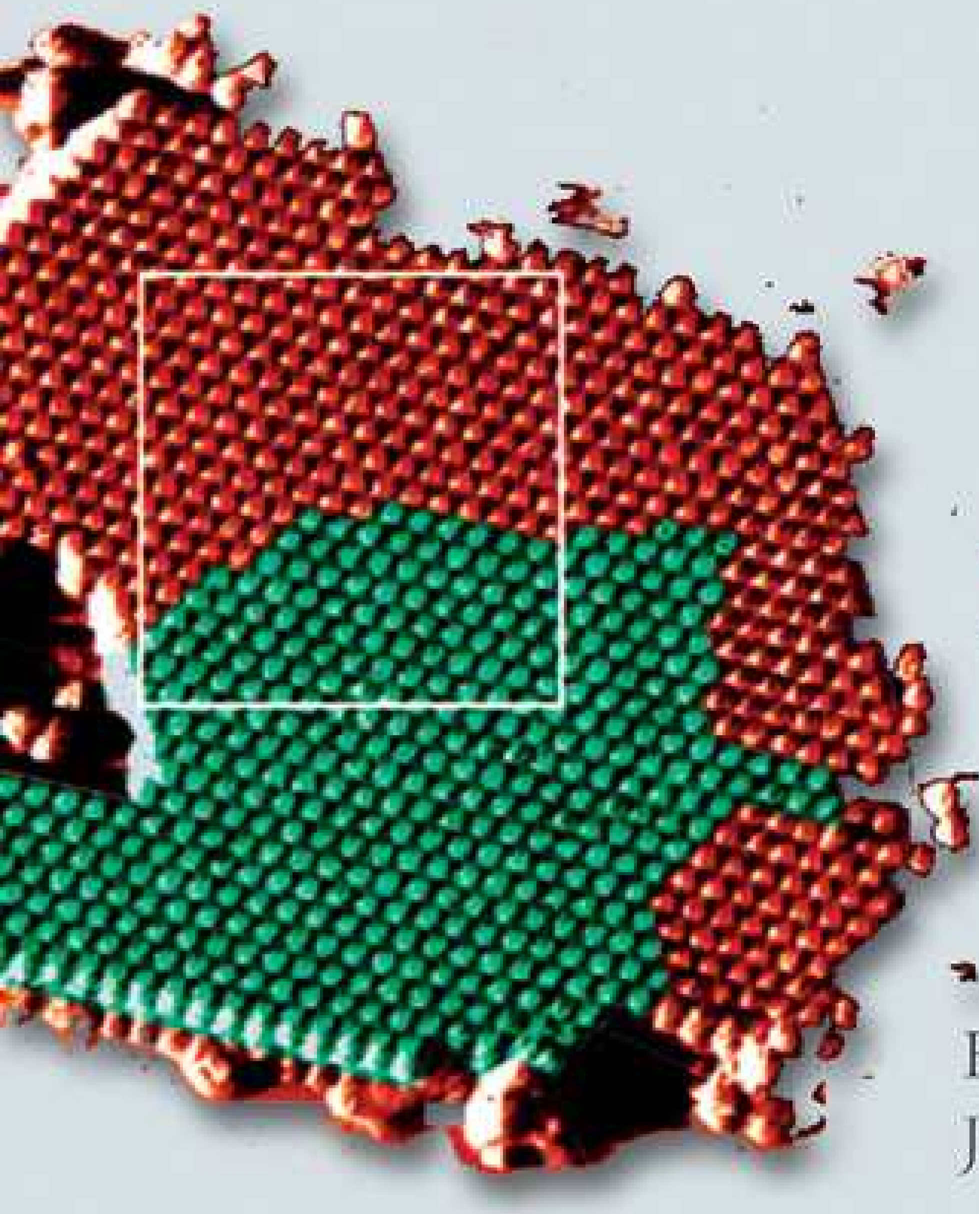

Feng Duan
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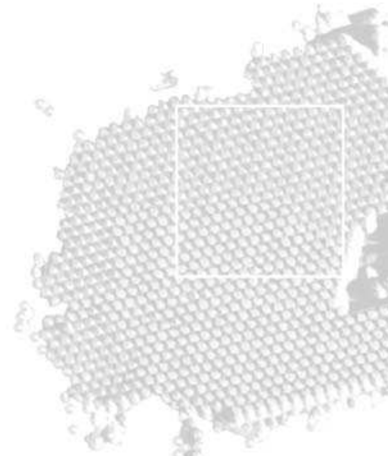
Introduction to Condensed Matter Physics

Volume 1



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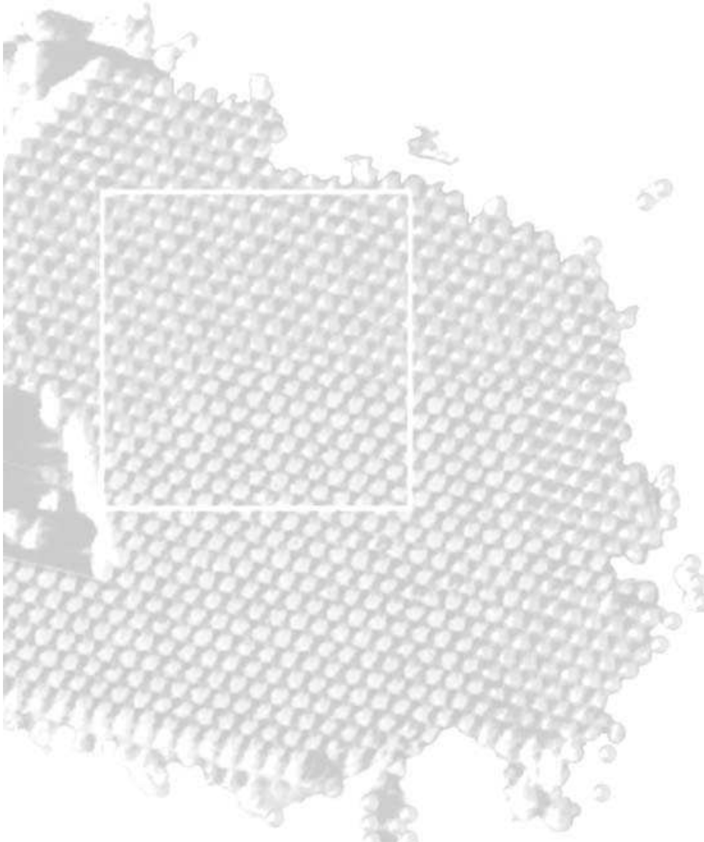

Introduction to Condensed Matter Physics

Volume 1

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Preface

Condensed matter physics is one of the most important, as well as most fertile, branches of contemporary physics. It is characterized by a multitude of research workers, a bewildering variety of research results, widespread influences on technical developments and rapid infiltrations into interdisciplinary areas. Historically, condensed matter physics has gradually evolved from solid state physics. However, due to the lack of a clear recognition of their inter-relationship (and the unfamiliarity with the new conceptual systems within the unifying theoretical framework introduced by condensed matter physics), though there are numerous excellent textbooks on solid state physics, a comprehensive introductory textbook on condensed matter physics is still waiting to appear. This unsatisfactory state of affairs is most clearly shown by the enormous gap between traditional textbooks on solid state physics and the frontier of present day research in condensed matter physics. It is a familiar sight to see students who have already taken courses in solid state physics (and even solid state theory) on approaching the frontier of condensed matter physics, for instance when browsing current issues of journals such as *Physical Review Letters*, who generally feel perplexed and alienated: They find the literature hard to understand. These difficulties in understanding do not stem principally from the derivation of the formulas or things related to experimental situations, the crux of the matter is that the mind is unprepared, so it is hard to comprehend why certain topics are chosen and whence the fundamental ideas descend. This situation has been realized by many eminent physicists who expressed the need to establish a graduate course to bridge the gap between traditional solid state physics and the research frontier. This course should be situated between two extremes: on the one hand, a traditional course which includes such long-standing subjects as the periodic structure, energy bands, and lattice dynamics, etc., comprehending these subjects and mastering their language prove to be indispensable to the students who wish to communicate scientifically. On the other hand, there are current topics, such as high T_c superconductivity, localization, quantum Hall effect, giant and colossal magnetoresistance, quantum dots, fullerenes and carbon nanotubes, photonic bandgap crystals, etc. Without touching these latter subjects they can hardly begin their research. Our book is just such an attempt to fill the gap between traditional solid state physics texts and the research frontier, and bears the name *Introduction to Condensed Matter Physics* to stress its introductory approach. There is bewildering variety and apparent complexity in contemporary condensed matter physics. However, due to the conceptual unity in the structure of matter, condensed matter physics can be organized into a coherent logical structure which is ripe for a systematic exposition in textbook form.

The basic concepts of condensed matter physics have been already penetratingly analyzed by P. W. Anderson in his monograph, "*Basic Notions of Condensed Matter Physics*", however, this book is for *cognoscenti*, perhaps too difficult for uninitiated graduate students. We acknowledge our indebtedness to this inspiring book, full of creative ideas, and try to make concrete some of these basic ideas, illustrating them with examples and placing them into suitable contexts. We were faced with the formidable task of assimilating and arranging this enormous mass of material into a satisfactory logical framework guided by a unifying conceptual framework, and finally incorporating it into a readable text. This text was originally intended for first year students of our graduate school, and some previous exposure to an undergraduate course in solid state physics is desirable but not necessary. In our institution, there is another course on condensed matter theory or solid state theory after this one, so in this course the physical concepts are stressed, simplified theoretical derivations are given to facilitate understanding, while cumbersome details of mathematics are avoided. Since condensed matter physics is closely linked to technological developments and interdisciplinary fields, we hope this book may also serve as a reference book for researchers in condensed matter physics, materials science, chemistry and engineering.

This book is organized into eight parts.

Part I gives the structural foundation of condensed matter physics. It starts from a brief resumé of classical crystallography. Its basic concepts such as symmetry and lattice are introduced and prepared for later generalization. Although the importance of symmetry is emphasized, complementary notions stemming from differential geometry and topology are also introduced to give a more rounded picture of structural crystallography and related topics. What follows may be called generalized crystallography; it means that the basic concepts of crystallography are generalized to cases in which the strict periodicity is absent, such as quasiperiodic structures, homogeneously disordered structures, supramolecular structures and inhomogeneous structures. Of course, statistical concepts such as order parameter, distribution functions and correlation functions are introduced to facilitate the treatment of various types of disordered structure. Mathematical aspects are introduced through Fourier transforms and other topics. Liquid crystals, self-assembled membranes, polymers and biopolymers are also discussed in order to help readers to explore the new field of soft condensed matter physics.

Part II embodies the results of carrying out the program based on the enlargement of the original paradigm of solid state physics. Starting from wave propagation in a periodic structure, besides briefly summarizing the basics of energy bands and lattice dynamics, an introduction of the photonic bandgaps is added; and wave behavior in quasiperiodic structures is also introduced. Then the dynamics of Bloch electrons and elementary treatment of transport properties including spin transport are given. It further leads to wave scattering by impurities and alloys, and after that, to wave localization due to disorder. More recent topics of quantum transport in mesoscopic systems have also been introduced. The unity of wave behaviors of different types of waves are emphasized through parallel treatments.

Part III may be taken as a duet between bond approach and band approach as well as a step towards many-body physics. These are based on the paradigms of quantum chemistry and solid state physics respectively. It is found that these two approaches are complementary to one another. Topics on electron correlation are introduced gradually, starting from Heitler and London's treatment of H_2 molecule, and finally reaching strongly correlated electronic systems with anomalous physical properties. This shows there are many important problems which lie beyond these two conventional approaches, some of them are still waiting to be solved. Finally current topics such as quantum confined nanostructures are discussed to illustrate the usefulness of these approaches in present day investigations. These first three parts may be regarded as the stage of transition from solid state physics to condensed matter physics.

Part IV deals with phase transitions and ordered phases. The Landau theory of second order phase transitions is introduced concurrently with the concepts of broken symmetry and order parameter. Then a lot of systems are discussed within this framework, such as crystals, quasicrystals and liquid crystals, which are the results of broken translational or rotational symmetry; ferromagnets or antiferromagnets, which are results of broken time reversal (or spin rotation) symmetry; and superfluids and superconductors, which are results of broken gauge symmetry. Finally, the concept of broken symmetry is generalized to include broken ergodicity for introducing the gas-liquid, wetting, glass, spin glass and metal-insulator transitions.

Part V deals with critical phenomena. After an introduction on fluctuations and related topics such as correlation and dissipation, the concepts of scaling and universality are formulated, and the renormalization group method is used to elucidate critical behaviors. Then the renormalization group method is applied to various other phenomena, such as percolation, localization of electrons, etc. Quantum critical phenomena are also discussed.

Part VI deals with elementary excitations. A general introduction, together with the scheme for classification of elementary excitations, is given. Then, more detailed discussions on vibrational excitations, magnetic excitations and electronic excitations follow, emphasizing those aspects which lie beyond conventional treatments. The theories of Fermi liquids, quantum Hall effect and Luttinger liquids are introduced and discussed.

Part VII deals with topological defects. These are nonlinear or topological excitations. Beginning from generalized elasticity and hydrodynamics, topological properties of defects are followed, then the structure and the energetics of defects, as well as the phases and the phase transitions associated with the defect assemblies, are described. Furthermore, the concept of generalized rigidity is introduced and used to elucidate those physical properties that are structure-sensitive.

It is reasonable to consider that the material from Part IV to Part VII forms the main body of condensed matter physics, unified by the concepts of broken symmetry and order parameter, and stratified according to the energy scale into different levels i.e., the ground states, the elementary excitations, the topological defects and the critical phenomena near T_c.

Part VIII may be regarded as an extension of condensed matter physics. It deals with physical kinetics and nonlinear phenomena in nonequilibrium states. The kinetics of phase transitions are introduced first, covering both second-order and first-order phase transitions; then the growth and form of crystalline materials follows, treating various facets of crystal growth; these provide the theoretical foundation for some crucial topics of materials science as well as an introduction to nonlinear phenomena. Then we treat nonlinear phenomena far from equilibrium in more detail: thermal convection is used as a classical example to illustrate the onset of hydrodynamic instability; then strange attractors and the routes to chaos are explained; finally, diverse phenomena involving spatio-temporal instabilities and pattern formation, such as avalanche and turbulence as well as some problems related to biology and technology are discussed. It shows that there is still a large number of problems in the neighborhood of condensed matter physics related to complexity, waiting to be explored and solved; it testifies that condensed matter physics today is still a flourishing subject.

This book will be published in two volumes: Vol. 1 contains Part I to Part IV, while Vol. 2 contains Part V to Part VIII. In general we assume that readers are already familiar with the basics of quantum mechanics and statistical physics. However different parts have different prerequisites, for instance, Part I, VI, VII and VIII as well as the first two chapters of Part IV can be read through even by those without any training in quantum mechanics. It is expected that this book may be used at different levels and for people with different areas of major interest. Each part may be read quite independently despite their interconnectedness. The whole book is intended as a text for a course in two semesters, while a sequence of selected parts may serve for a one semester course.

We would like to make some comparisons with existing textbooks in this field. Since the publication of *Modern Theory of Solids* by F. Seitz in 1940, many excellent textbooks on solid state physics have appeared. Among them: Kittel's *Introduction to Solid State Physics* is most popular, it has run into numerous editions; while Ashcroft and Mermin's *Solid State Physics* is noted for its painstaking effort in clarifying basic concepts. However, due to the limitation of the conceptual framework, these texts do not communicate many important basic concepts as well as as catch up to the flowering richness of contemporary condensed matter physics. In recent years, a few graduate texts bearing the title condensed matter physics have appeared. We admire these pioneering attempts and have read them with much interest and profit. However, in our opinion or prejudice, they are not entirely satisfactory because they are either not comprehensive enough to cover this broad field, or not systematic enough to give a precise idea about basic concepts threading through them. In this book we try to give a pedagogically understandable exposition on the basic concepts of condensed matter physics illustrated with many concrete physical problems, as well as to give a comprehensive and coherent picture of the contemporary scene, thereby bridging the gap between the traditional texts of solid state physics and the current literature scattered throughout physics journals. Condensed matter physics gradually unfolds in this book from more traditional parts of solid state physics, its basic concepts are emphasized and carefully explained, most equations are derived with not too complicated mathematics, in order to be accessible to first year graduate students and research workers, especially for experimental workers.

Since 1983, one of the authors, Duan Feng, had been seriously concerned with the clarification of the conceptual framework of condensed matter physics and had written a number of articles to expound it. Since 1989, this new approach had been thoroughly discussed and illustrated with various current topics at the frontier of this field in a series of lectures. Then, in collaboration with the other author, Guojun Jin, a book "*New Perspective on Condensed Matter Physics*" (in Chinese) was written and published in 1992. Beginning in 1990 a graduate course called *Introduction to Condensed*

Matter Physics was established in the Physics Department of Nanjing University jointly by the authors. More recently, the teaching of this course in Nanjing University has been done singly by Guojun Jin. Courses for the *Summer School on Condensed Matter Physics* in 1996 (organized by Tsinhua and Peking University, Beijing) and in 1998 (organized by Nanjing University, Nanjing) have been jointly given by the authors. Based on the lecture notes for these courses used over many years, the manuscript for this book gradually evolved. Everyone recognizes that the field of condensed matter physics has exploded in recent years and we have chosen an impossible task: New and significant research results emerge every day. Thus, we can only apologize for overlooking some topics and trust that the reader will understand the difficult task we have set for ourselves. We invite criticism and advice on how to improve this book.

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Duan Feng and Guojun Jin
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