THE PHYSICS AND CHEMISTRY OF MATERIALS

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The City College of the City University of New York

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For Harriet and Françoise

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PREFACE

As science has become more interdisciplinary and impinges ever more heavily on technology, we have been led to the conclusion that there is a great need now for a textbook that emphasizes the physical and chemical origins of the properties of solids while at the same time focusing on the technologically important materials that are being developed and used by scientists and engineers. A panel of physicists, chemists, and materials scientists who participated in the NSF Undergraduate Curriculum Workshop in Materials in 1989, which addressed educational needs and opportunities in the area of materials research and technology, issued a report that indicated clearly the need for advanced textbooks in materials beyond the introductory level. Our textbook is meant to address this need.

This textbook is designed to serve courses that provide engineering and science majors with their first in-depth introduction to the properties and applications of a wide range of materials. This ordinarily occurs at the advanced undergraduate level but can also occur at the graduate level. The philosophy of our approach has been to define consistently the structure and properties of solids on the basis of the local chemical bonding and atomic order (or disorder!) present in the material. Our goal has been to bring the science of materials closer to technology than is done in most traditional textbooks on solid-state physics. We have stressed properties and their interpretation and have avoided the development of formalism for its own sake. We feel that the specialized mathematical techniques that can be applied to predict the properties of solids are better left for more advanced, graduate-level courses.

This textbook will be appropriate for use in the advanced materials courses given in engineering departments. Such courses are widely taught at the junior/senior level with such titles as "Principles of Materials Science & Engineering," "Physical Electronics," "Electronics of Materials," and "Engineering Materials." This textbook is also designed to be appropriate for use by physics and chemistry majors. We note that a course in materials chemistry is a relatively new one in most chemistry undergraduate curricula but that an introductory course in solid-state physics has long been standard in physics undergraduate curricula.

To gain the most benefit from courses based on this textbook, students should have had at least one year each of introductory physics, chemistry, and calculus, along with a course in modern physics or physical chemistry. For optimal use of the textbook it would be helpful if the students have had courses in thermodynamics, electricity and magnetism, and an introduction to quantum mechanics.

As the title indicates, the range of topics covered in this textbook is quite broad. The 21 chapters are divided into five sections. The range of topics covered is comprehensive, but not exhaustive. For example, topics not covered in detail due to lack of space include biomaterials, a field with a bright future, and composites, examples of which are discussed only within specific classes of materials. Much more material is presented than can be covered in a one-semester course. Actual usage of the text in courses will be discussed after the proposed subject matter has been outlined.

Following an introduction, which emphasizes the importance of materials in modern science and technology, Section I, on the "Structure of Materials," consists of four chapters on the structure of crystals, bonding in solids, diffraction and the reciprocal lattice, and order and disorder in solids.

Section II, on the "Physical Properties of Materials," consists of six chapters on phonons; thermally activated processes, phase diagrams, and phase transitions; electrons in solids: electrical and thermal properties; optical properties; magnetic properties; and mechanical properties.

Section III, titled "Classes of Materials," consists of eight chapters on semiconductors; metals and alloys; ceramics; polymers; dielectric and ferroelectric materials; superconductors; magnetic materials; and optical materials. In each chapter the distinctive properties of each class of materials are discussed using technologically-important examples from each class. In addition, the structure and key properties of selected materials are highlighted. In this way an indication of the wide spectrum of materials in each class is presented.

Section IV, titled "Surfaces, Thin Films, Interfaces, and Multilayers," consists of two chapters covering these important topics. Here the effects of spatial discontinuities in the physical and chemical structure on the properties of materials are presented, both from the point of view of creating materials with new properties and also of minimizing the potential materials problems associated with surfaces and interfaces.

Section V, titled "Synthesis and Processing of Materials," consists of a single chapter. Representative examples of how the structure and properties of materials are determined by the techniques used to synthesize them are presented. "Atomic engineering" is stressed. The tuning of structure and properties using postsynthesis processing is also illustrated.

Problem sets are presented at the end of each chapter and are used to emphasize the most important concepts introduced, as well as to present further examples of important materials. Illustrations are employed for the purpose of presenting crystal structures and key properties of materials. Tables are used to summarize and contrast the properties of related groups of materials. The units used throughout this textbook are SI units, except in cases where the use of electron volt, cm^{-1}, poise, etc., were felt to be too standard to ignore.

We have created a home page at www.wiley.com that provides a valuable supplement to the textbook by describing additional properties of materials, along with additional examples of current materials and their applications. Chapter W22 on our home page emphasizes the structural and chemical characterization of materials, as well as the characterization of their optical, electrical, and magnetic properties. As new materials and applications are developed, the home page will be regularly updated.

Since this text will likely be used most often in a one-semester course, we recommend that Chapters 1–4 on structure be covered in as much detail as needed, given the backgrounds of the students. A selection of chapters on the properties of materials (5–10) and on the classes of materials (11–18) of particular interest can then be covered. According to the tastes of the instructor and the needs of the students, some of the remaining chapters (surfaces; thin films, interfaces, and multilayers; synthesis and processing of materials) can be covered. For example, a course on engineering materials could consist of the following: Chapters 1–4 on structure; Chapter 6 on thermally activated processes, etc.; Chapter 10 on mechanical properties; Chapter 12 on metals and alloys; Chapter 13 on ceramics; Chapter 14 on polymers; and Chapter 21 on synthesis and processing.

Physics majors usually take an introductory course in solid-state physics in their senior year. Therefore in such a course it will be necessary to start at "the beginning," i.e., Chapter 1 on the structure of crystals. Students in MS&E or engineering departments who have already taken an introductory course on materials can quickly review (or skip) much of the basic material and focus on more advanced topics, beginning with Chapter 5 on phonons, if desired, or Chapter 7 on electrons in solids.

We owe a debt of gratitude to our colleagues at The City College and City University who, over the years, have shared with us their enthusiasm for and interest in the broad and fascinating subject of materials. They include R. R. Alfano, J. L. Birman, T. Boyer, F. Cadieu, H. Z. Cummins, H. Falk, A. Genack, M. E. Green, L. L. Isaacs, M. Lax, D. M. Lindsay (deceased), V. Petricevic, F. H. Pollak, S. R. Radel, M. P. Sarachik, D. Schmeltzer, S. Schwarz, J. Steiner, M. Tamargo, M. Tomkiewicz, and N. Tzoar (deceased). Colleagues outside CUNY who have shared their knowledge with us include Z. L. Akkerman, R. Dessau, H. Efstathiadis, B. Gersten, Y. Goldstein, P. Jacoby, L. Ley, K. G. Lynn, D. Rahoi, and Z. Yin. Our thanks also go to our students and postdocs who have challenged us, both in our research and teaching, to refine our thinking about materials and their behavior.

Special thanks are due to Gregory Franklin who served as our editor at John Wiley & Sons for the bulk of the preparation of this textbook. His unflagging support of this effort and his patience are deeply appreciated. Thanks are also due to our current editor, George Telecki, who has helped us with sound advice to bring this project to a successful conclusion. We acknowledge with gratitude the skill of Angioline Loredo who supervised the production of both the textbook and supplementary Web-based material. We have appreciated the useful comments of all the anonymous reviewers of our textbook and also wish to thank all the authors who granted permission for us to use their artwork.

Finally, we gratefully acknowledge the constant support, encouragement, and patience of our wives, Harriet and Françoise, and our families during the years in which this textbook was prepared. Little did we (or they) know how long it would take to accomplish our goals.

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LIST OF TABLES