# Physical Properties *of* Materials

## Second Edition

Mary Anne White

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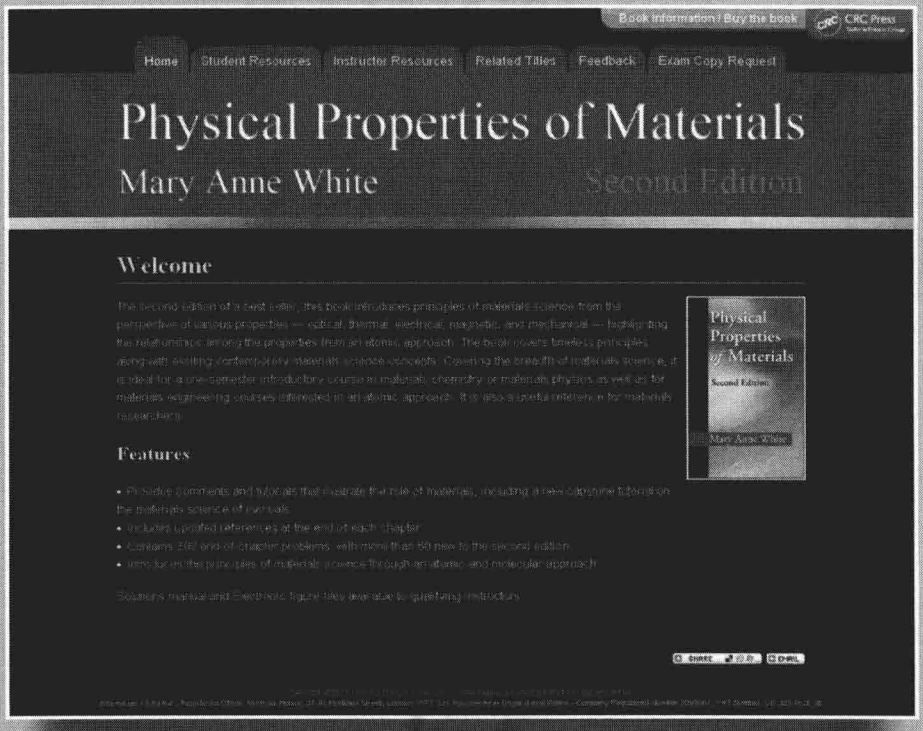
## *Interactive Companion Website*




**The website offers a wealth of ancillary resources for students and instructors that enhance the material in the text.**

***Student Resources:***

- Updates to the Further Reading sections
- Links to relevant movies and podcasts for each chapter
- Video demonstrations of thermochromism, the thermoelectric effect, memory metal, magnetic levitation with superconductors, and more
- Additional problems and errata

***Instructor Resources:***

- Sources of demonstration materials for lectures
- PowerPoint slides of figures from the book
- Solutions manual
- A link to request an exam copy

**www.physicalpropertiesofmaterials.com**

*Dedicated to my first teachers, my parents*

# *Preface to the Second Edition*

Materials science offers a wonderful opportunity to introduce students to basic principles of matter through forefront research topics of immediate or near-future direct application to their lives.

Materials research is advancing rapidly. New topics in this second edition include materials and sustainability, carbon nanotubes, other nanomaterials such as nanocomposites, quantum dots, spintronics, and magnetoresistance. In addition, in response to comments from other professors who taught from the first edition, this new edition includes an introductory section on structures of materials and more discussion concerning polymers.

All aspects of the text have been edited and revised to correct some minor shortcomings in the first edition, and to clarify points where readers kindly indicated a need. The format is similar to the first edition in that the text is brought alive through Comments and Tutorials that illustrate the role of materials in our lives. In this second edition, several new Comments and a new cap-stone Tutorial on the materials science of cymbals have been added. References at the ends of chapters, to be used by the reader for further depth, have also been updated. In addition, more than 60 new end-of-chapter problems have been added, bringing the total number of problems to 300. To guide students through the myriad equations, a margin marker for the most important equations has been introduced in this second edition.

Since 1991, I have been teaching a materials science course at the junior (third-year) undergraduate level, cross-listed as a chemistry/physics course. Initially I taught with the notes that became the first edition, and then I taught from the first edition, most recently supplanted with additional information that is now in the second edition. This is a 13-week course, with three hours of lectures per week. Within that envelope, I also include Tutorials.* For the most part, I cover all the topics, in the order of the textbook. Sometimes in my lectures I have to omit or abbreviate topics, and, if so, what is covered in Chapters 10 and/or 11 is reduced. Mostly, I include the introductory parts of Chapter 14 after presenting Chapter 5, so the students have a foreshadowing of the importance of mechanical properties. This course has now been enthusiastically taken by about 800 students, mostly in chemistry and physics programs, but also in engineering, earth science, and biochemistry, and they frequently comment on how much they appreciate the links to their everyday lives. I have managed to find lecture demonstrations for each and every lecture, many from everyday life. And I enjoy learning more examples from the students!

* For details concerning presentation, see M. A. White, 1997. Tutorials as a teaching method for materials science. *Journal of Materials Education*, 19, 23–26.

The background colors on the front cover were produced by viewing a CD case through crossed polarizers, with backlighting. See Chapter 14 for discussion of color from stress-induced polarization.

We will encounter many equations in this book. The most important are designated with ▮ to the left of the equation.

Finally, to emphasize that this book concerns the physical properties of materials, the word "physical" has been added to the first-edition title of *Properties of Materials*.

A website for *Physical Properties of Materials* is maintained by the publisher. Further updates and contact information for reader suggestions are available at www.physicalpropertiesofmaterials.com.

Enjoy learning about physical properties of materials!

**Mary Anne White**
*Halifax, Nova Scotia, Canada*

# *Preface to the First Edition*

The idea for this book germinated at a public lecture in about 1989. The lecturer had mentioned in passing, "and you all know how a photocopier works." Most of the remainder of the lecture was lost on me, in wondering what fraction of that educated audience knew how a photocopier worked. Then I began to realize that there was no place in our curriculum where such an important concept was taught to our students. After that lecture I decided to take advantage of revision of the physical chemistry curriculum going on in my department at that time, to prepare a curriculum for a class based on properties of materials. The class was launched in 1991. Finding no appropriate textbook, I wrote out my lecture notes for the students to use. With subsequent revisions and additions, these have become the book before you.

The purpose of this book is to introduce the principles of materials science through an atomic and molecular approach. In particular, the aim is to help the reader to learn to think about properties of materials in order to understand the principles behind new (or old) materials. A "perfect goal" would be for the reader to be able to learn about a new material in the business pages of the daily newspaper, giving minimal scientific information, and from that decipher the scientific principles on which the use of the material is based.

Properties of materials have interested many people. When speaking of his youth, Linus Pauling* said: "I mulled over the properties of materials: why are some substances colored and others not, why are some minerals or inorganic compounds hard and others soft."† It is noteworthy that such deep considerations of the world around us eventually led Pauling to make seminal contributions in many areas. It is hoped that encouragement of wonder in the variety and nature of properties of materials will be of benefit to those who read these pages.

This textbook should be viewed as an introductory survey of principles in materials science. While this book assumes basic knowledge of physical sciences, many of the concepts are presented with introductory mathematical and theoretical rigor. This is largely to refrain from use of tensors (avoided in all but a few places) in this presentation; the interested reader will find more detailed presentations and derivations in the bibliography.

This book is divided into parts based on various properties of materials. After a general introduction to materials science issues, origins of colors and other optical properties of materials are considered. The next part concerns thermal properties of materials, including thermal stability and phase

* Linus Pauling (1901–1994) was an American chemist and winner of the 1954 Nobel Prize in Chemistry for research into the nature of the chemical bond and its applications to elucidation of structure of complex substances. Pauling also won the 1962 Nobel Peace Prize.

† John Horgan, 1993. Profile: Linus Pauling. *Scientific American*, March 1993, 36.

diagrams. A further part is about electrical and magnetic properties of materials, followed by a final part on mechanical stability.

This book has been used for the basis of a one-semester class in materials science, offered in a chemistry department, and taken by students in chemistry, biochemistry, physics, engineering, and earth sciences. The prerequisite for the class is prior introduction to the laws of thermodynamics.

A feature of this book is the introduction of tutorials, in which the students, working in small groups, can apply the principles exposed in the text to work out for themselves the physical principles behind applications of materials science.

An Instructors' Supplement, containing complete discussion of all the points raised in the tutorials, and complete worked solutions to all the end-of-chapter problems, is available through the publisher to instructors who have chosen the book for class use.

This book has aimed to present the principles behind various properties of materials and, since it is a survey of a large subject, additional reading suggestions are given at the end of each chapter as sources of more detailed information. References to recent developments also are given, in order to expose the readers to the excitement of current materials science research. Updates to these references will be made available through the publisher's Web site, www.physicalpropertiesofmaterials.com.

The presentation for this book is by type of property—optical, thermal, electrical, magnetic and mechanical. Types of materials—metals, semiconductors (intrinsic and extrinsic), insulators, glasses, orientationally disordered crystals, defective solids, liquid crystals, Fullerenes, Langmuir-Blodgett films, colloids, inclusion compounds, and more—are introduced through their various properties. As new types of materials are made or discovered, it is hoped that the approach of exposing principles that determine physical properties will have a lasting effect on future materials scientists and many others.

# *Acknowledgments*

This book has been helped through the comments of many people, especially those who have taught from the first edition, and those who have used it as students at Dalhousie University and elsewhere all around the world. I hope that readers will help me to continue to refine this text by bringing suggestions for improvement and inclusion to my attention.

I particularly want to thank N. Aucoin, P. Bessonette, R. J. C. Brown, R. J. Boyd, W. Callister, P. Canfield, D. B. Clarke, A. Cox, J. Dahn, S. Dimitrijevic, R. Dumont, A. Ellis, J. E. Fischer, H. Fortier, J. M. Honig, M. Jakubinek, N. Jackson, B. Kahr, C. Kittel, B. London, M. Marder, T. Matsuo, M. Moskovits, K. Nassau, G. Nolas, N. Pelot, R. Perry, L. Schramm, J.-M. Sichel, E. Slamovich, T. Stevens, T. Swager, I. Tamblyn, and M. Tan for constructive comments. Special thanks to A. Inaba for detailed comments as a result of his translation of the first edition to Japanese, and to chemistry/music student P. MacMillan, who introduced me to the materials science of cymbals. Thanks also to M. LeBlanc for preparation of most of the diagrams for the first edition, and to J. E. Burke, D. Eigler, F. Fyfe, Ch. Gerber, M. Gharghouri, M. Jericho, C. Kingston, A. Koch, M. Marder, K. Miller, J.-M. Phillipe, R. L. White, and K. Worsnop for photographs or other assistance with graphical contributions. I thank the Dalhousie University Faculty of Science for a teaching award that made it possible to hire assistance for the first edition. In addition, I am grateful to S. Gillen, J. S. Grossert, K. J. Lushington, M. Meyyappan, A. J. Paine, D. G. Rancourt and R. L. White for providing useful information, and to members of my current research group, A. Bourque, C. Bryan, A. Cerqueira, L. Desgrosseilliers, K. Miller, M. Johnson, A. Ritchie, C. Romao and C. Weaver, for assistance reading proofs. Thanks also to Jill Jurgensen, Joette Lynch, Allison Shatkin and the other staff at CRC Press for excellent support.

Writing a book takes time. My now-grown children, David and Alice, have never really known a time when I was not working on this book! For their forbearance while I have been preoccupied, I sincerely thank my family, especially my husband Rob, as this would not have been accomplished without his loving support.

# *About the Author*

**Mary Anne White** is an active materials research chemist and a highly recognized educator and communicator of science. Dr. White presently holds the distinguished title of University Research Professor at Dalhousie University, Halifax, Nova Scotia, Canada, where she has been since 1983, after receiving a BSc in honors chemistry from the University of Western Ontario, a PhD in chemistry from McMaster University, and a postdoctoral fellowship at Oxford University. From 2002 to 2006, she was the founding director of the Institute for Research in Materials at Dalhousie University, and since 2010 she has been director of the multidisciplinary graduate program, Dalhousie Research in Energy, Advanced Materials and Sustainability (DREAMS).

Dr. White's research area is energetics and thermal properties of materials. She has made significant contributions to understanding how heat is stored and conducted through materials. Her work has led to new materials that can convert waste heat to energy, and materials that can trap solar energy. Her research contributions have been recognized by national and international awards, and she is an author of more than 130 research papers and several book chapters. She also is the editor for materials science for the *McGraw-Hill Encyclopedia of Science and Technology*. She has trained more than 30 graduate students and postdoctoral fellows, and more than 50 undergraduate research students.

Dr. White enjoys sharing her knowledge with students and with the general public. She is especially well known for presenting clear explanations of difficult concepts. Mary Anne's outstanding abilities as an educator have been recognized by the Union Carbide Award for Chemical Education from the Chemical Institute of Canada. Mary Anne has given more than 150 invited presentations at conferences, universities, government laboratories, and industries around the world.

Dr. White has been active throughout her career in bringing science to the general public. This includes helping establish a hands-on science center; many presentations for schools, the general public and others (including a lecture for members of Canada's parliament and senate); booklets on science activities for children (published by the Canadian Society for Chemistry); serving as national organizer of National Chemistry Week; more than 150 articles for educators or the general public; and appearances on television. Since 2001, she has been a regular contributor on CBC Radio's "Maritime Noon," where she and a colleague field listeners' science questions, live on

air to an audience of about 20,000. For her contributions to public awareness of science, Mary Anne was awarded the 2007 McNeil Medal of the Royal Society of Canada. In 2008 she received a Doctor of Science (honoris causa) from McMaster University, her PhD alma mater.

> Knowledge comes, but wisdom lingers.
>
> **Alfred Lord Tennyson**

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