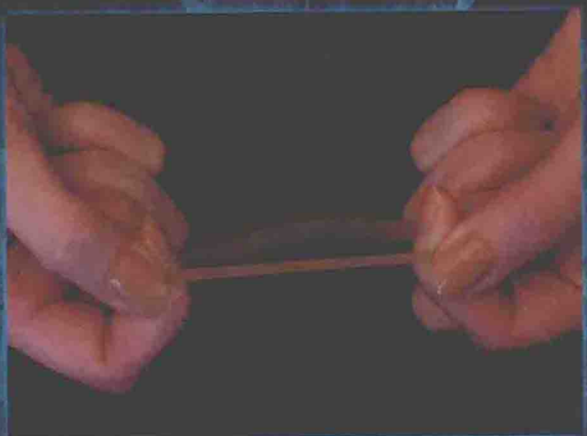
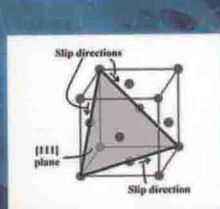
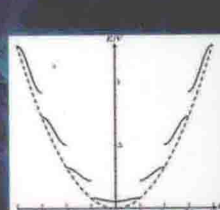
Understanding Solid State Physics







Sharon Ann Holgate

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Dedication

*In memory of my grandmother Louisa Edmondson,
and my friend John Wilson.*

Preface

I first came up with the idea for this book when I was a postgraduate student, and was working part-time as a teaching assistant for my physics department. I could see a lot of undergraduates struggling to understand their courses simply because they were unable to grasp the basic principles behind the various topics. It seemed to me that this was partly because many textbooks assumed a prior knowledge and mathematical aptitude that not all of their readers had, and which was obscuring the main points very early on in the explanation process. From that moment of realisation onwards, I wanted to write a truly accessible solid state physics textbook for introductory courses that concentrated on explaining the basics, and gave students a firm grounding in the subject. It was also very important to me to relate the theories and concepts to the real world, so that anyone reading it could see the point of learning the physics and how it was likely to be used once they had left university.

To help achieve these objectives, I have endeavoured to highlight the technological applications of the physics being discussed and to point out the multidisciplinary nature of much scientific research. I have also tried to keep the number of equations to a minimum wherever possible, in the hope that this will allow the book to provide a useful introduction to solid state physics for any physics and materials science undergraduates who feel daunted by a highly mathematical approach. The mathematics that does appear is presented in small logical steps, and problems are tackled as worked examples, in the hope that if an ex-maths struggler like myself can understand it like that, everyone else who is baffled will understand it too! The small number of more complicated derivations that were impossible to avoid are also presented in a step-by-step fashion in an appendix.

I hope this approach will also aid students or researchers in other scientific disciplines who may cross over into the field at some stage. With readers like the geologists and geographers I used to work alongside in a thermoluminescence laboratory in mind, in addition to the maths appendix, I have included some short appendices on related physics topics.

After spending the last decade working as a freelance journalist and broadcaster, I felt it was important to include some magazine-style boxes on interesting research. This allowed me to cover topics that might otherwise not feature in a textbook of this size, and also to give some idea of what it is like researching either in industry or academia. Cowriting my first book (with the late Robin Kerrod), a picture-based popular science book for children, has also influenced this project in the respect that I was keen to include images that I hope will inspire, and in some cases amuse.

The questions with answers overleaf are intended to help readers test their knowledge as they make their way through the book, and should prove equally useful for revision. Further questions can be found on the accompanying website, and there is a solutions manual available for qualifying instructors. The website also houses a light-hearted video quiz for readers, and downloadable supplementary material including further references for reading and web links. Finally the book includes a glossary of widely used terms, and I have used underlining to highlight the first instance of each use throughout the main text.

Writing this book has reminded me of a story about a magic pudding that I enjoyed reading as a child. This was a pudding with attitude. He walked about on skinny legs with his bowl on his head, and waved his fists at his enemies when they tried to eat him. But he had no need to be so aggressive because his magical powers meant that when anyone ate a slice of him, he re-formed into a complete round pudding again. In a similar way, just when I thought I had finished writing a section of this book, the remainder seemed to re-form into a whole book waiting to be written, as there were so many more things that had come into my mind that I wanted to include. However, despite the frustrations that the sheer size of the project produced, I have now, I hope, achieved my original aims.

I am indebted in no small way to Alan Piercy, who having taught solid state physics for over 30 years probably thought he would escape the subject in his retirement. Instead, he has spent the last few years as my academic advisor, steering me in the right direction, answering my myriad of questions, and putting up with my occasional rants when things went awry. I would also like to thank the friends and colleagues—including Jim Al-Khalili, John Barrow, Bill Buckley, Sue Bullock, Sue Crossfield, David Culpeck, Nicki Dennis, Colin Humphries, Steve Keevil, Peter Main, David Mowbray, Derek Palmer, Manoj Patairiya, John and Alan Robbins, Tom Spicer, Dianne Stilwell, and Tracey and Alice de Whalley—who have helped in various ways to make this book possible.

Thanks are also due to the many press officers at institutions and companies, including Amanda Bowie at the U.S. Naval Research Laboratory, Kathryn Klein from Lakeland Limited, Jane Koropsak at Brookhaven National Laboratory, Keith Lumley at Network Rail, and Leigh Rees at Oxford Diffraction, who have aided my quest for interesting photographs and have kindly provided additional information. I extend similar thanks to all the researchers around the world who have kindly given permission for me to write about their work, and feature their results.

My third editor, John Navas, has provided an immeasurable amount of support and advice during the last two years of this project, and my heartfelt thanks go to him. In addition, my mother Joan and friends—including Dawson Chance, Larry Crockett, Andrew Fisher, Amanda Kernot, David King, Julian Mayers, Darren Naylor, Ian Rennison, and Emma Winder—have provided a welcome distraction at evenings and weekends, and prevented me from becoming even more obsessed with solid state physics than I was before I began writing this.

Sharon Ann Holgate, Sussex, U.K., 2009

Corrections:
Whilst great care and much time has been taken in the creation of this book, mistakes may have slipped through the net, and any corrections or suggestions for improvement can be sent to: John.Navas@informa.com

Author

Sharon Ann Holgate has a DPhil in physics from the University of Sussex, where she is a Visiting Fellow in physics and astronomy. She has worked for over a decade as a science writer and broadcaster, with 50 broadcast appearances including presenting on the BBC World Service and BBC Radio 4, and competing in a 'Boffins Special' of The Weakest Link. Her numerous articles have appeared in *New Scientist*, *The Times Higher Education Supplement*, *E&T*, *Flipside*, *Focus*, *Physics World*, *Interactions*, *Modern Astronomer*, and *Astronomy Now*, while her first book, *The Way Science Works* (coauthored with Robin Kerrod) was shortlisted for the Royal Society Junior Books Prize. She has also written and developed brochures, national careers material, and press releases for various scientific institutions, and given talks at venues including the Science Museum in London. Dr. Holgate was the Institute of Physics Young Professional Physicist of the Year for 2006, awarded for her "passionate and talented promotion of physics and the public perception of physics through her books, articles, talks and broadcast work".

Further Acknowledgements

With special thanks to Alan Piercy and David Culpeck for their assistance with the line diagrams.

Hand and foot modelling (images 1.3, 4.7, and part (d) of Example question 4.4): the author.

Contents

1 Introduction

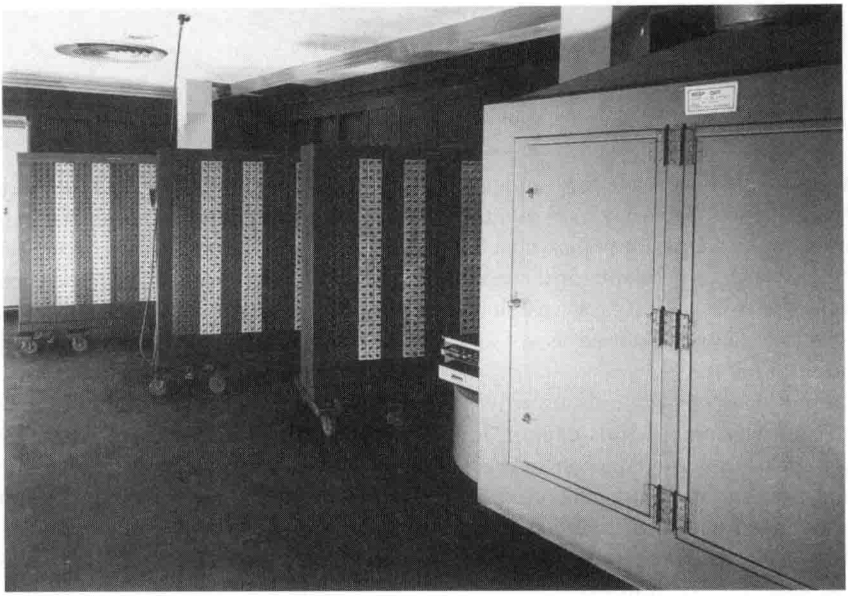
It is impossible to escape solid state physics. Solids are all around us, and their properties affect our everyday lives in many ways from the mundane to the sophisticated. For example, we can only pick up a hot metal saucepan if it has a handle made of an insulator such as a plastic, or if we wrap our hands in a thick cloth, because metals conduct heat so well. By contrast, it is the piezoelectric properties of certain crystals that allow them to be used as sensors on bridges to warn engineers of impending structural failure.

Solid state physics tells us why some solids can conduct heat and electricity well and why other solids cannot. It explains magnetism, the ways in which light and other types of radiation interact with solids, and reveals the processes that enable electronic components and devices to work. It also tells us how the atoms are arranged within different types of solids, and how the tiny forces holding the atoms in these arrangements affect much larger scale properties of solids such as melting point and hardness.

In some ways research in the field of solid state physics can move forward relatively slowly, and it certainly lacks the glamour that, say, the discovery of a new subatomic particle or a new M-class planet brings. But when solid state physics does produce an important result, the seemingly small step can have a major influence on all our lives. It is unlikely, for instance, that the group of people witnessing a demonstration of the transistor on a December day in 1947 could have predicted the size and influence of the modern electronics industry that would result from this invention.

Of course in electronics as in many other fields, there has been considerable progress in the last 50 years. The continuing decrease in the sizes of transistors and other circuit components—brought about not only by experimental work, but also by theoretical studies revealing information such as the influence of impurities on the semiconductor materials circuit components are made from—has allowed computer chips to become faster and faster. Smaller components also mean more information can be stored in a given space. These improvements in processing speed and data storage have allowed new products including mobile phones and digital cameras to be developed, as well as helping enable computers to shrink from the size of a room to something we can balance on our laps (see Figure 1.1). And if nanotechnology—the building of materials, structures, and devices on the nanometre scale by manipulating individual atoms and molecules—lives up to its promises, laptop computers will soon seem as large and cumbersome to us as those early mainframe computers.

Progress in solid state physics can actually be charted quite well by improvements in computer technology. An understanding of the optical properties of liquid crystals, and an ability to manufacture them on an industrial scale, made flat-screen displays for laptops, electronic organisers, and calculators possible. In addition, the discovery of powerfully magnetic rare earth materials has created a decrease in the



(a)

(b)

FIGURE 1.1 One of the world's first electronic computers, the UNIAC (a) (U.S. Army Photo). By the mid 1990s, 5 million transistors could be fitted onto a silicon chip that you could balance on your fingertip, and there were electronic organisers on the market no larger than early calculators. Chips are now many times smaller than an ant (b) (© Philips.)

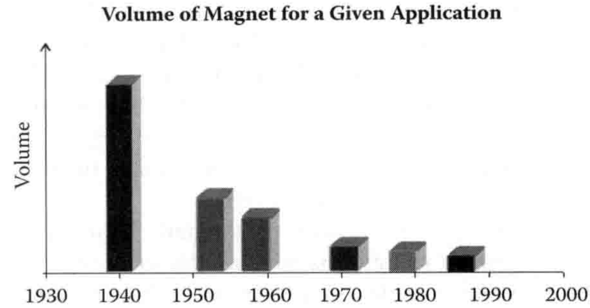


FIGURE 1.2 A decrease in the size of permanent magnets, made possible by the discovery of more and more powerful magnetic materials over the last 50 years, has enabled small electric motors to be developed. These have applications ranging from car windscreen wipers and electric toothbrushes to magnetic storage devices such as computer hard disks and video recorders.

size of permanent magnets (see Figure 1.2) and so allowed much smaller electric motors to be designed. This enabled devices including hard disks, floppy disks, CDs, and DVDs to be developed—which use tiny motors to spin the disk when reading and writing—and replace cumbersome magnetic tape for computer data storage. However, CDs and DVDs would not have been possible without another breakthrough in solid state physics: the invention of the diode laser.

Nowadays we think nothing of using a laser pointer when giving a presentation (see Figure 1.3), and while magnetic tape is still used for both audio and video recording, compact discs have become standard for audio recording, while DVDs provide high-quality video recording. These devices use tiny solid-state diode lasers made from semiconductor materials to write and read data, but just a few decades ago—before enough was understood about semiconductors and the way they interact with light—the only lasers that existed were huge gas or crystal lasers confined to

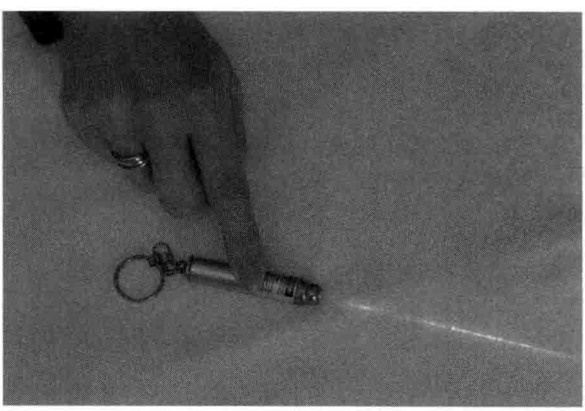


FIGURE 1.3 A laser pointer is now an everyday article, but years ago the only lasers were laboratory-based devices.

laboratories. The next generation of so-called "quantum dot" lasers should be even smaller than solid-state lasers, which could lead to a whole new range of optoelectronic devices and applications. It is also likely that we will see a range of new applications in the future for an existing optoelectronic device—the light-emitting diode (LED). Improvements in the brightness and cost of LEDs are leading us to the point where they are becoming viable as a replacement for conventional tungsten light bulbs for domestic lighting, and can be used for traffic lights.

In order to make new types of devices, new manufacturing methods have to be developed. Epitaxial growth techniques, which allow electronic components to be built up layer by layer, have made a huge impact by helping make the continued development of smaller electronic components possible. Meanwhile, new ways of growing crystals, and of making other materials such as composites and polymers, have enabled a range of modern materials to replace more traditional choices in many applications; for example, plastic bottles are now more widely used than glass for soft drinks. There have also been improvements in manufacturing more traditional materials. In fact it was the ability to produce high-quality glass that made optical fibres a practical proposition for the telecommunications industry.

Important as all these developments have been, there are many other areas in which solid state physics has already made a significant impact on our lives, and in which huge improvements may only be a short time away. The ongoing quest for higher temperature superconductors is a good example, as it could eventually lead to domestic power cables with almost no resistance, while further development of solar cells may also help reduce the amount of nonrenewable energy we use.

It is hard to predict what breakthroughs solid state physics will produce in the next few decades, but one thing seems certain. As we all become increasingly dependent on technology, it is likely that this fascinating area of physics will play an important part in providing the sort of future our societies will demand.