Engineering Solids

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Engineering solids

To Jean, James, Daniel, Edward, Gwilym
and in memory of Brychan

Preface

This book originated from a course of the same title that is given to first-year electrical engineering students at the University of Surrey. The course serves as an introduction to ideas in areas outside their own narrow topic, but many of the concepts introduced are used later in their physical electronics course. My interest in the subject is based on my experience as a researcher in solid-state physics and also as an industrial metallurgist.

The text has been developed from this nucleus and widened in scope in order to serve as an introduction to aspects of solids of interest to students in other engineering disciplines. It is hoped that the book may, in addition, be valuable as a pre-college introductory text for those intending to study pure science.

The approach has grown out of my own frustrations as a physics student, when I found that one had to become immersed in the details of the subject, the maths, in order to pass exams.

In many cases, the exciting ideas were obscured by the detail until much later. This seems the wrong way of going about things, and this book is an attempt to adopt the opposite approach. The challenge has been to introduce the models without using mathematics, and to integrate the physics with that other important facet of solids, materials science.

The aim was to be concerned solely with ideas, concepts. One may say never mind the width, appreciate the quality. The hope is that if, subsequently, the student comes to measure the width with his mathematical tape measure, he will appreciate what goes into the fabric and how it can be made into a useful garment.

Mathematics has been successfully banished, except for a few relationships and one proof. The proof is included not because it is good for the soul, but to serve as an example of how elegant mathematics can be, and to show how necessary it is in any quantitative description of the physical world.

Integration (of the non-mathematical variety) has not been entirely achieved, the book still falls into two parts: the physics of solids and the science of materials. Perhaps this is the nature of the beast or beasts, but the first two chapters serve as a common base for both parts.

The book is not intended as a reference, to be dipped into to extract facts. *It is meant to be read*. Care was taken to adopt a progressive approach; to tell the story of solids. The simplest model that will explain the phenomenon is always used and every model is developed from one used earlier in the book.

I hope by this means that an interest and understanding of solids will be kindled which, perhaps, will inspire the student to pursue the subject further and in more depth. Even if this aim is not achieved, one hopes, at least, that some insight into how scientists see the physical world has been given, and some of the questions why? and how? have been answered in a simple way.

Finally, I would like to thank Jill Singleton and her colleagues for the enormous help they have given me with the typing and organization of the manuscript. I would also like to thank Ken Stephens and my other colleagues of the Department of Electronic and Electrical Engineering for help and encouragement. For photographs used in the book, I have to thank Jim Whitton of the University of Copenhagen, Peter Goodhew and his colleagues from the Department of Materials Science at the University of Surrey, Peter Hemment of my own department, and the Materials Research Corporation.

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Contents

Part 1

Atomic Bonding and Crystal Structures

'See plastic nature working to this end,
The single atoms each to other tend.
Attract, attracted to, the next in place,
Form'd and impell'd its neighbour to embrace.'

('An Essay on Man', by Alexander Pope)

1. The nature of atoms and the atomic bond

1.1 Introduction

In this book, we will progress from a description of the way atoms congregate to form solids (Part 1) to an introduction to the concepts behind our understanding of the properties of solids (Parts 2 and 3). Finally, Part 4 deals with the ways in which the properties of solids are controlled (one may say engineered) to create materials of use to the technologist.

Models (mathematical or diagrammatical) are used by scientists to describe the physical world that we cannot directly sense, and, therefore, cannot really know in human terms. The models that will be adopted in this book will be the simplest that can be used to describe the phenomena of interest in a non-mathematical way.

We start, in this chapter, with a description of the atomic structure. Once this has been established, the wave nature of sub-atomic particles is discussed by analogy with more familiar vibrating systems (for example, the vibrating string). Using these analogies, the quantization of energy is introduced and the periodic electron configuration of the atom is described. The correspondence between this and the chemical nature of atoms, as evidenced by the periodic table of elements, is then explained.

Armed with this information, we are able to describe the ways in which a bond between two atoms can be formed: the first step in the creation of a solid.

1.2 The atomic structure

The atom is the smallest unit that retains the properties attributable to a particular element. The atom is, therefore, the basic building block of matter.

Rutherford, in 1911, used the bombardment of metal foils with α particles† to investigate the structure of the atom. Although it was known that the atomic

† An α particle is the nucleus of a helium atom.

diameter was of the order of 1 angstrom (1 angstrom is equivalent to 10^{-10} m),† the deflection of these small projectiles by the atoms in a foil told Rutherford that almost all the mass of the atom was concentrated in a region roughly 10^{-4} Å in diameter. This strongly scattering region was called the nucleus of the atom.

The α particles pass right through the majority of the atom without deflection, but something must occupy this space. The reason for saying this is the fact that, when atoms interact to form solids, they arrange themselves in regular arrays, every nucleus being separated from its neighbours by a distance of approximately 1 Å. In fact, the space around the nucleus is occupied by electrons. Our story of solids is mainly that of the electrons; it is they which interact to form the atomic bonds that hold the solid together. In addition, it is the electron configuration that controls the electrical, magnetic, thermal, optical, and mechanical properties of materials.

To introduce atomic structure, we must also consider the nucleus. Therefore, let us split the atom and probe briefly into the world of sub-atomic or elementary particles.

Many elementary particles are now known to inhabit the nucleus; they are involved in creating the nuclear forces. However, it is not the aim of this book to explain the nature of nuclear forces. For a description of atomic structure, we will be safe in making the simplifying assumption that the nucleus is only occupied by two types of elementary particle: the proton and the neutron.

The mass and electrical charge of the three atom-building particles are listed in Table 1.1. We can see that the proton and neutron have approximately the same mass and are about two thousand times heavier than the electron. The nucleus will, therefore, be massive, in agreement with Rutherford's interpretation of the α-particle scattering.

The proton and the electron have equal and opposite charge. This is the smallest unit of electrical charge that can exist, and charge must always be in

Table 1.1 The elementary particles

Name	Approximate mass (atomic mass units)	Charge
Proton	1	$+e$
Neutron	1	0
Electron	0.0005	$-e$

1 atomic mass unit = 1.66×10^{-27} kg.
The charge on an electron, $e = 1.60 \times 10^{-19}$ coulombs

†The angstrom is not a recognized SI unit. However, because it is 'atom sized', it is used in this text for its convenience. It is, in fact, still widely used in many scientific disciplines.

Table 1.2 The first seven isotopes

Name	Symbol	Protons (= electrons), Z	Neutrons N	Mass number, A	Abundance in nature (per cent)
Hydrogen	^{1}H	1	0	1	~100
Deuterium	^{2}H	1	1	2	0.015
Tritium	^{3}H	1	2	3	*
Helium	^{3}He	2	1	3	0.000 13
	^{4}He	2	2	4	~100
	^{6}He	2	4	6	*
	^{8}He	2	6	8	*

*Indicates that the isotope is unstable.

integral amounts of this quantity. This is our first encounter with the 'lumpiness' of properties at an atomic level. We will see later that energy also comes in lumps which are called quanta.

Atoms in equilibrium are electrically neutral; the number of electrons is equal to the number of protons. The number of protons is called the atomic number and is given the symbol Z. It is the value of Z that determines the chemical nature of an atom. When $Z = 1$, we have a hydrogen atom with the chemical symbol H; for $Z = 2$, helium (He); for $Z = 3$, lithium (Li); and so on up to uranium (U) with $Z = 92$, the most massive naturally occurring element.†

You may ask: why do we need neutrons? In fact, neutrons are essential for the stability of the nucleus; it is the interaction between neutrons and protons that produces the enormous force that holds the nucleus together against the electrical repulsion between the positively charged protons. The number of neutrons (N) approximately equals the number of protons (Z) for the light atoms; for heavier atoms, N approaches 1.5 Z.

For any particular value of Z, it is possible to have atoms with different numbers of neutrons. These atoms with the same Z, having therefore an identical number of electrons and an identical chemical nature, differ only with respect to the mass of the nucleus. They are called *isotopes* and are normally represented by writing ^{A}X, where X is the chemical symbol (implying a particular value of Z) and A is the total number of particles in the nucleus, i.e., $A = N + Z$; A is called the mass number. The values of Z, N, and A for the isotopes of hydrogen and helium are listed in Table 1.2. Hydrogen is unique in two ways. The most commonly occurring isotope, ^{1}H, has no neutrons in the nucleus (with only one proton, nuclear forces are not needed to stabilize the nucleus). Also, the two other isotopes have their own names and are sometimes given the symbols D and T, although they are chemically identical to hydrogen. Heavy water, which is used in nuclear reactors, is the oxide of deuterium (D_2O instead of H_2O).

†Heavier atoms up to and perhaps beyond $Z = 101$ have been synthesized by man.