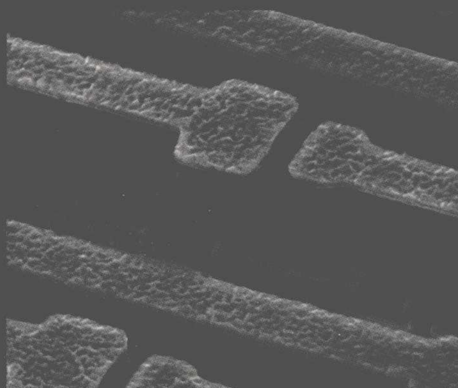
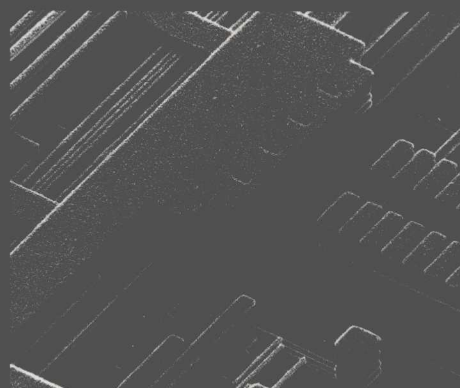
Second Edition

Principles of
Electronic Materials and Devices





S.O. Kasap

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SECOND EDITION

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PREFACE

SECOND EDITION

The textbook represents a first course in electronic materials and devices for undergraduate students. With the additional topics in the text's CD-ROM, it can also be used in a graduate introductory course in electronic materials for electrical engineers and material scientists. The second edition is an updated and revised version of the first edition based on reviewer comments, with new topics such as *conduction in insulators, Hall effect in semiconductor, phonons,* and *thermal properties;* new problems; a number of new worked examples; and a new chapter on the *optical properties of materials.* The second edition is one of the few books on the market that has a broad coverage of electronic materials that today's scientists and engineers need. I believe that the revisions have improved the rigor without sacrificing the original semiquantitative approach that both the students and instructors liked.

ORGANIZATION AND FEATURES

In preparing the text, I tried to keep the general treatment and various proofs at a semiquantitative level without going into detailed physics. Many of the problems have been set to satisfy engineering accreditation requirements. Some chapters in the text have additional topics to allow a more detailed treatment, usually including quantum mechanics or more mathematics. Cross referencing has been avoided as much as possible without causing too much repetition, which allows for various sections to be skipped as desired by the reader.

Some important features are

- The principles are developed with the minimum of mathematics and with the emphasis on physical ideas. Quantum mechanics is part of the course but is presented without its difficult mathematical formalism.
- There are more than 130 worked examples, most of which have a practical significance. Students learn by way of examples, however simple, and to that end nearly 150 problems have been provided.
- Even simple concepts have examples to aid learning.
- Most students would like to have clear diagrams to help them visualize the explanations and understand concepts. The text includes numerous illustrations (over 470) that have been professionally prepared to reflect the concepts and aid the explanations in the text.
- The end-of-chapter questions and problems are graded so that they start with easy concepts and eventually lead to more sophisticated concepts. Difficult problems are identified with an asterisk (*). Many practical applications with diagrams have been included. There is a regularly updated on-line extended *Solutions Manual* for all instructors; simply locate the McGraw-Hill website for this textbook.
- There is a glossary, *Defining Terms,* at the end of each chapter that defines some of the concepts and terms used, not only within the text but also in the problems.
- The end of each chapter includes a section *Additional Topics* to further develop important concepts, to introduce interesting applications,

or to prove a theorem. These topics are intended for the keen student and can be used as part of the text for a two-semester course.

- The text is supported by McGraw-Hill's textbook website that contains resources, such as solved problems, for both students and instructors.

Please feel free to write to me with your comments. Although I may not be able to reply to each individual comment and suggestion, I do read all my e-mail messages and take note of suggestions and comments. If you like the text and would like to see a third edition, which takes time to prepare, please send your comments for revisions and changes to the Electrical Engineering Editor, McGraw-Hill, 1333 Burr Ridge Parkway, Burr Ridge, IL 60521, USA.

CD-ROM ELECTRONIC MATERIALS AND DEVICES: SECOND EDITION

The book has a CD-ROM that contains all the figures as large *color diagrams* in a common portable document format (PDF) that can be printed on nearly any color printer to make overhead projector transparencies and class-ready notes for the students so they won't have to draw the diagrams during the lectures. The diagrams have been also put into *PowerPoint* for directly delivering the lecture material from a computer. In addition, there are numerous *Selected Topics* and *Solved Problems* to extend the present coverage. For example, *Elementary Mechanical Properties* allows instructors to include this topic in their courses. *Semiconductor Fabrication* now appears as a selected topic in the CD. I strongly urge students to print out the CD's *Illustrated Dictionary of Electronic Materials and Devices: Student Edition,* to look up new terms and use the dictionary to refresh various concepts. This is probably the best feature of the CD.

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"The important thing in science is not so much to obtain new facts as to discover new ways of thinking about them."

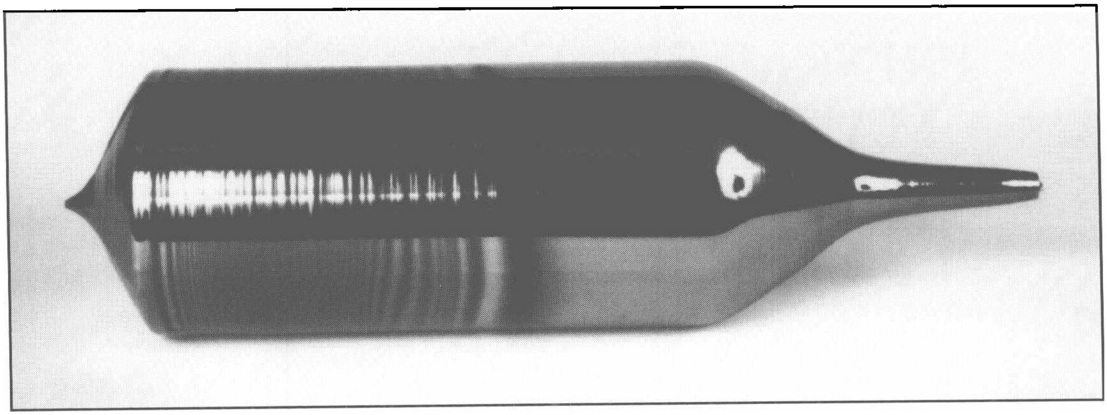
Sir William Lawrence Bragg

To Güler, my mother; Nicolette, my wife; and Alp, my dad

BRIEF CONTENTS

CONTENTS

PRINCIPLES OF ELECTRONIC MATERIALS AND DEVICES



A single crystal of silicon, a silicon ingot, grown by the Czochralski technique. The diameter of the ingot is 6 inches.
| SOURCE: Courtesy of Texas Instruments.

GaAs ingots and wafers.
| SOURCE: Courtesy of Sumitomo Electric Industries, Ltd.

CHAPTER

1

Elementary Materials Science Concepts[1]

Understanding the basic building blocks of matter has been one of the most intriguing endeavors of humankind. Our understanding of interatomic interactions has now reached a point where we can quite comfortably explain the macroscopic properties of matter, based on quantum mechanics and electrostatic interactions between electrons and ionic nuclei in the material. There are many properties of materials that can be explained by a classical treatment of the subject. In this chapter, as well as Chapter 2, we treat the interactions in a material from a classical perspective and introduce a number of elementary concepts. These concepts do not invoke any quantum mechanics, which is a subject of modern physics and is introduced in Chapter 3. Although many useful engineering properties of materials can be treated with hardly any quantum mechanics, it is impossible to develop the science of electronic materials and devices without modern physics.

1.1 ATOMIC STRUCTURE

The model of the atom that we must use to understand the atom's general behavior involves quantum mechanics, a topic we will study in detail in Chapter 3. For the present, we will simply accept the following facts about a simplified, but intuitively satisfactory, atomic model called the **shell model,** based on the **Bohr model** (1913).

The mass of the atom is concentrated at the nucleus, which contains protons and neutrons. Protons are positively charged particles, whereas neutrons are neutral particles, and both have about the same mass. Although there is a Coulombic repulsion

[1] This chapter may be skipped by readers who have already been exposed to an elementary course in materials science.

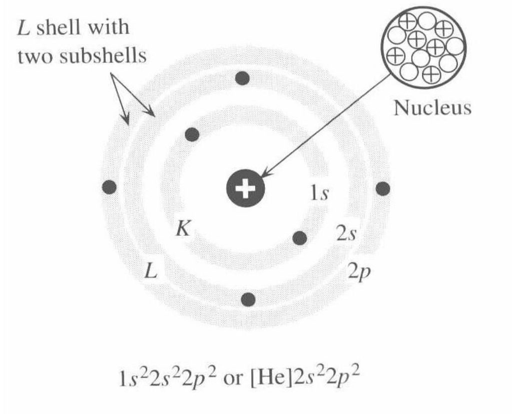


Figure 1.1 The shell model of the carbon atom, in which the electrons are confined to certain shells and subshells within shells.

between the protons, all the protons and neutrons are held together in the nucleus by the **strong force,** which is a powerful, fundamental, natural force between particles. This force has a very short range of influence, typically less than 10^{-15} m. When the protons and neutrons are brought together very closely, the strong force overcomes the electrostatic repulsion between the protons and keeps the nucleus intact. The number of protons in the nucleus is the **atomic number** Z of the element.

The electrons are assumed to be orbiting the nucleus at very large distances compared to the size of the nucleus. There are as many orbiting electrons as there are protons in the nucleus. An important assumption in the Bohr model is that only certain orbits with fixed radii are stable around the nucleus. For example, the closest orbit of the electron in the hydrogen atom can only have a radius of 0.053 nm. Since the electron is constantly moving around an orbit with a given radius, over a long time period (perhaps $\sim 10^{-12}$ seconds on the atomic time scale), the electron would appear as a spherical negative-charge cloud around the nucleus and not as a single dot representing a finite particle. We can therefore view the electron as a charge contained within a spherical **shell** of a given radius.

Due to the requirement of stable orbits, the electrons therefore do not randomly occupy the whole region around the nucleus. Instead, they occupy various well-defined spherical regions. They are distributed in various shells and **subshells** within the shells, obeying certain occupation (or seating) rules.[2] The example for the carbon atom is shown in Figure 1.1.

The shells and subshells that define the whereabouts of the electrons are labeled using two sets of integers, n and ℓ. These integers are called the **principal** and **orbital angular momentum quantum numbers,** respectively. (The meanings of these names are not critical at this point.) The integers n and ℓ have the values $n = 1, 2, 3, \ldots$, and $\ell = 0, 1, 2, \ldots, n-1$, and $\ell < n$. For each choice of n, there are n values of ℓ, so higher-order shells contain more subshells. The shells corresponding to $n = 1, 2, 3, 4, \ldots$

[2] In Chapter 3, in which we discuss the quantum mechanical model of the atom, we will see that these shells and subshells are spatial regions around the nucleus where the electrons are most likely to be found.

Table 1.1 Maximum possible number of electrons in the shells and subshells of an atom

		Subshell			
		$\ell = 0$	1	2	3
n	Shell	s	p	d	f
1	K	2			
2	L	2	6		
3	M	2	6	10	
4	N	2	6	10	14

are labeled by the capital letters $K, L, M, N, \ldots$, and the subshells denoted by $\ell = 0, 1, 2, 3, \ldots$ are labeled $s, p, d, f\ldots$. The subshell with $\ell = 1$ in the $n = 2$ shell is thus labeled the $2p$ subshell, based on the standard notation $n\ell$.

There is a definite rule to filling up the subshells with electrons; we cannot simply put all the electrons in one subshell. The number of electrons a given subshell can take is fixed by nature to be[3] $2(2\ell + 1)$. For the s subshell ($\ell = 0$), there are two electrons, whereas for the p subshell, there are six electrons, and so on. Table 1.1 summarizes the most number of electrons that can be put into various subshells and shells of an atom. Obviously, the larger the shell, the more electrons it can take, simply because it contains more subshells.

The number of electrons in a subshell is indicated by a superscript on the subshell symbol, so the electronic structure, or configuration, of the carbon atom (atomic number 6) shown in Figure 1.1 becomes $1s^2 2s^2 2p^2$. The K shell has only one subshell, which is full with two electrons. This is the structure of the inert element He. We can therefore write the electronic configuration more simply as $[He]2s^2 2p^2$. The general rule is put the nearest previous inert element, in this case He, in square brackets and write the subshells thereafter.

The electrons occupying the outer subshells are the farthest away from the nucleus and have the most important role in atomic interactions, as in chemical reactions, because these electrons are the first to interact with outer electrons on neighboring atoms. The outermost electrons are called **valence electrons** and they determine the **valency** of the atom. Figure 1.1 shows that carbon has four valence electrons in the L shell.

When a subshell is full of electrons, it cannot accept any more electrons and it is said to have acquired a stable configuration. This is the case with the inert elements at the right-hand side of the Periodic Table, all of which have completely filled subshells and are rarely involved in chemical reactions. The majority of such elements are gases inasmuch as the atoms do not bond together easily to form a liquid or solid. They are sometimes used to provide an inert atmosphere instead of air for certain reactive materials.

[3] We will actually show this in Chapter 3 using quantum mechanics.

Example 1.1 **VIRIAL THEOREM** In a system of charges in which the only interactions are electrostatic attractions and repulsions, there is a very simple relation between the average values of the potential energy PE, kinetic energy KE, and the overall energy E for the charges:

Virial theorem

$$\overline{KE} = -\tfrac{1}{2}\overline{PE} \quad [1.1]$$

In addition, the total energy is the sum of kinetic and potential energies, so

Total average energy

$$\overline{E} = \overline{PE} + \overline{KE} \quad [1.2]$$

The virial theorem can be applied to atoms as well as molecules provided that the only interactions are electrostatic (Coulombic type). Consider the hydrogen atom in Figure 1.2. The ionization energy of the hydrogen atom is 13.6 eV.

a. It takes 13.6 eV to ionize the hydrogen atom, i.e., to remove the electron to infinity. If the condition when the electron is far removed from the hydrogen nucleus defines the zero reference of energy, then the total energy of the electron within the H atom is −13.6 eV. Calculate the average PE and average KE of the electron.

b. Assume that the electron is in a stable orbit of radius r_o around the positive nucleus. What is the Coulombic PE of the electron? Hence, what is the radius r_o of the electron orbit?

c. What is the velocity of the electron?

d. What is the frequency of rotation (oscillation) of the electron around the nucleus?

SOLUTION

a. Using Equation 1.1 in Equation 1.2 we obtain

$$\overline{E} = \overline{PE} + \overline{KE} = \tfrac{1}{2}\overline{PE}$$

or

$$\overline{PE} = 2\overline{E} = 2 \times (-13.6\text{ eV}) = -27.2\text{ eV}$$

The average kinetic energy is

$$\overline{KE} = -\tfrac{1}{2}\overline{PE} = 13.6\text{ eV}$$

b. The Coulombic PE of interaction between two charges Q_1 and Q_2 separated by a distance r_o, from elementary electrostatics, is given by

$$PE = \frac{Q_1 Q_2}{4\pi\varepsilon_o r_o} = \frac{(-e)(+e)}{4\pi\varepsilon_o r_o} = -\frac{e^2}{4\pi\varepsilon_o r_o}$$

Figure 1.2 The planetary model of the hydrogen atom in which the negatively charged electron orbits the positively charged nucleus.