



Principles of
**Electrical
Engineering
Materials and
Devices**



S. O. Kasap

PRINCIPLES OF ELECTRICAL ENGINEERING MATERIALS AND DEVICES

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

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PRINCIPLES OF ELECTRICAL ENGINEERING MATERIALS AND DEVICES

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He has recently been awarded the Doctor of Science degree from the University of London for his contributions to materials science in electrical engineering and electrophotography. He is a Fellow of the Institution of Electrical Engineers, the Institute of Physics, and the Institute of Materials; and he is a registered professional engineer in Canada and the European Union.

Concepts form the basis for any science. These are ideas, usually somewhat vague (especially when first encountered), which often defy really adequate definition. The meaning of a new concept can seldom be grasped from reading a one-paragraph discussion. There must be time to become accustomed to the concept, to investigate it with prior knowledge, and to associate it with personal experience. Inability to work with details of a new subject can often be traced to inadequate understanding of its basic concepts.

William C. Reynolds, *Thermodynamics*
(New York: McGraw-Hill, 1968, now out of print)

PREFACE

Over the last two decades, there have been dramatic advances in semiconductors; and many Electrical Engineering (EE), Materials Science, and Engineering Physics departments have introduced extensive courses on semiconductors, particularly on the fabrication of microelectronic devices. There are now many excellent texts on the subject. The first course in materials is generally taught by non-electrical engineers in other departments. In all these courses, the mechanical properties, fracture, phase diagrams, phase transformations, metals, alloys, steels and cast irons, ceramics, glasses, plastics, and composites are greatly overemphasized, and usually the students do not satisfactorily cover electrical engineering materials and applications of materials in the EE discipline. The first materials course is generally followed by an EE course in semiconductor materials and devices that invariably includes extensive semiconductor physics. The consequence has been an overemphasis in mechanical properties and semiconductors. In many cases, dielectric and magnetic properties have been either underrepresented or totally bypassed.

We are now realizing the importance of having a first course that covers EE materials in a general way that also includes dielectric and magnetic properties. This was the rationale in preparing the current text. Over the next five to ten years, many Electrical Engineering, Materials Science, and Physics departments will be looking for a materials text at the junior level that covers a broad spectrum of electrical materials, includes dielectric and magnetic materials, has applications and extensive problems, has elementary quantum mechanics, and has

an overall goal of satisfying various accreditation requirements across international borders. This textbook should answer these needs.

Organization and Features

The text represents a *first* course in electrical engineering materials and devices suitable for one- or two-semester courses at the second- or third-year level of a four-year curriculum. It can either follow a short elementary materials science course or can be used on its own as a starting text. This is not a specialized text in electronic materials emphasizing semiconductor physics and technology. There are many books in the market in this field.

The organization of the text allows it to be used for both one or two semester courses. Some chapters have additional topics to allow a more detailed treatment, usually including quantum mechanics or more mathematics. The text may be used in short or extended (two-semester) courses according to the instructor's choice of chapters and sections. Cross referencing has been avoided as much as possible to reduce "student irritation" to an acceptable level without too much repetition and to allow various sections to be skipped as desired by the reader.

The majority of the problems have been solved on software math packages (Theorist and Mathcad) that will be available to the instructor. I chose to divide the material into eight chapters based on my personal experience with the students. They felt more comfortable in covering something in every chapter rather than leaving out whole chapters in a course.

When a whole chapter is skipped, they tend to feel that they missed out on an important topic and feel a loss of continuity. I currently use the text in a two-semester EE materials course.

I tried to keep the general treatment and various proofs at a semiquantitative level without going into detailed physics. On the one hand, we are required to cover as much as possible and, on the other hand, professional engineering accreditation requires students to solve numerical problems and carry out “design calculations.” In preparing the text, I tried to satisfy B.Sc. Engineering accreditation requirements in as much breadth as possible. Many of the problems have been set to satisfy engineering accreditation requirements. Obviously one cannot solve numerical problems, carry out design calculations, and at the same time derive each equation in a text without exploding the size of the text to an unacceptable level.

Some important features:

- The principles are developed with the minimum of mathematics and with the emphasis on physical ideas. Quantum mechanics is part of the course but without its difficult mathematical formalism.
- There are more than 120 worked examples, most of which have a significance in electrical engineering. Students learn by way of examples, however simple, and to that end more than 130 problems have been provided.
- Even the simplest concepts have examples to endow a feeling of fulfillment in the student.
- Most students would like to have clear diagrams to help them visualize the explanations and understand concepts. The text includes numerous illustrations (427 original diagrams, figures, and graphs) that have been computer drafted 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. All of these problems have been classroom tested and have been solved on Theorist and/or Mathcad. There is a detailed *Solutions Manual* for the instructor.
- Some of the end-of-chapter problems also instill the idea of concurrent engineering, which requires the student to apply several concepts simultaneously from various diverse fields even though they may not have covered some of the topics in detail.
- There is a glossary, “Important 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 on “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.

This book is supported by the author’s Web site (<http://Kasap3.Usask.Ca>), which contains additional worked examples, additional topics, color photographs, more illustrations, an extended glossary of *Defining Terms in Electronic Materials and Devices*, links to other materials science Web sites, a list of interesting reading material (helpful for term papers), tables of useful materials data, a corrigendum page, and an extensive reading list with comments. No undergraduate book can claim originality, and I have benefitted from many excellent books. These are listed in Web site with the author’s comments.

Prerequisites

The level of sophistication has been kept at the junior undergraduate level where the students have not seen quantum mechanics or any elementary materials science. Indeed, this would be their first exposure to quantum mechanics. They would have been exposed to first-year physics and chemistry courses covering only classical concepts. Their mathematical level is assumed to include ordinary differentiation and integration but to exclude partial differentiation. It is quite likely that partial differentiation is covered in a math class in the same semester. Partial differentiation occurs only in the Schrödinger equation in Chapter 3, where it is simply treated as if it were ordinary differentiation but with respect to one of the variables. For those students who have taken an elementary class in materials science (van Vlack, *Elements of Materials Science*, or a similar text), a suitable starting point is Chapter 2.

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consuming and arduous nature of running experimental research laboratories at the same time as having a heavy teaching load and, throughout his headship, kept a tight lid on my administrative duties (i.e., almost none). With his frequent visits to my office and research labs, Ron kept on encouraging me and thereby unwittingly initiated the whole project.

Various reviewers at one time or another read various portions of the manuscript and provided extensive comments. I incorporated the majority of the suggestions, which I believe make this a better book. I'd like to personally thank them all for their invaluable critiques, some of whom include:

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chapter

1

Elementary Materials Science Concepts¹

Understanding the basic building blocks of matter has been one of the most intriguing endeavors of mankind. 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 the next, 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 its 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 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

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

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 $n = 1, 2, 3, \dots$, and $\ell = 0, 1, 2, \dots, n - 1$, and $\ell < n$. For each choice of n , there are n values of ℓ , so higher-order shells contain more subshells. The shells

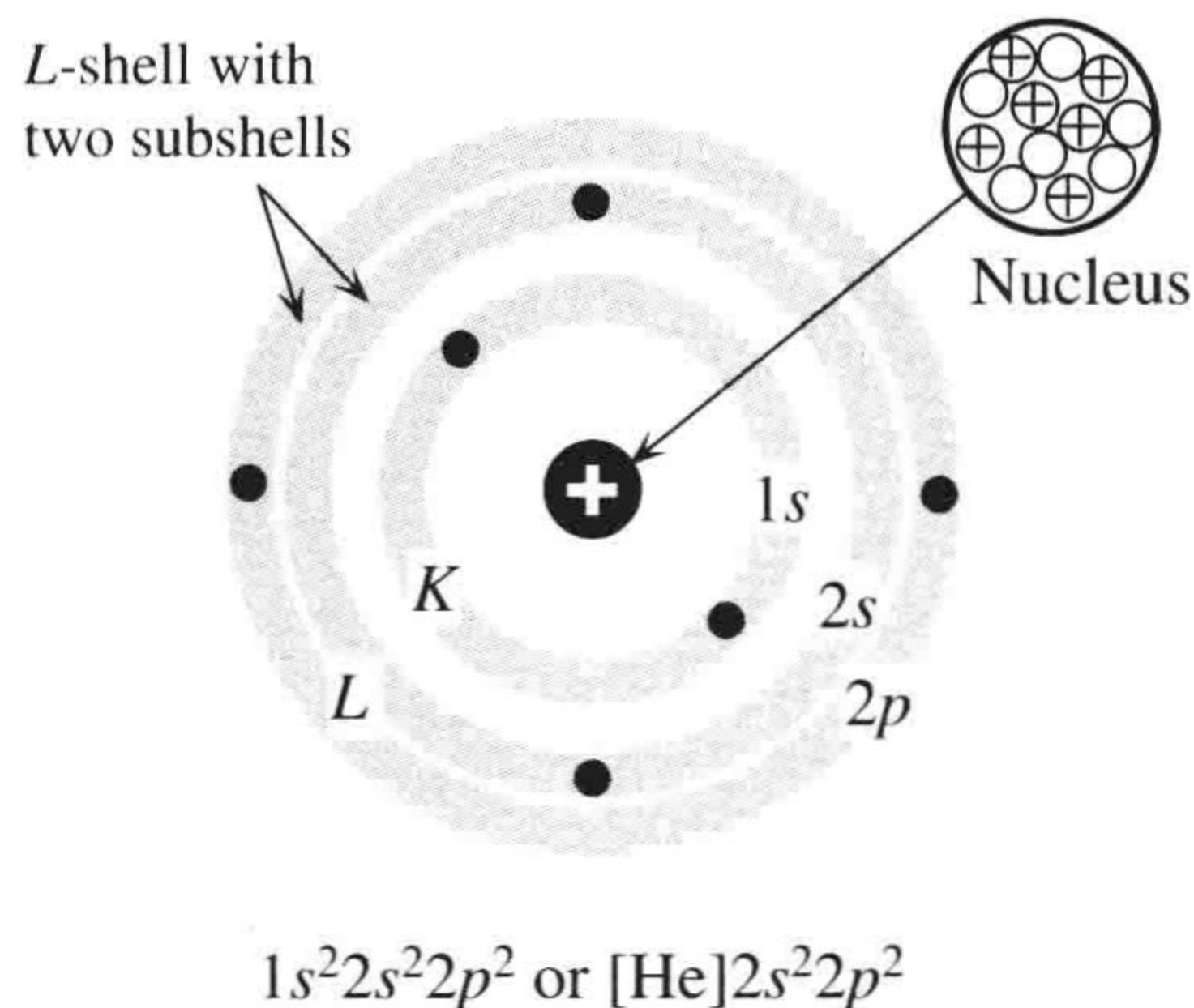


Figure 1.1 The shell model of the carbon atom, in which the electrons are confined to certain shells and subshells within shells.

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.

corresponding to $n = 1, 2, 3, 4, \dots$ are labeled by the capital letters K, L, M, N, \dots , and the subshells denoted by $\ell = 0, 1, 2, 3, \dots$ are labeled s, p, d, f, \dots . 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 $2(2\ell + 1)$. For the s subshell ($\ell = 0$), there are 2 electrons, whereas for the p subshell, there are 6 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 $[\text{He}]2s^2 2p^2$. 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.

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

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

¹ We will actually show this in Chapter 3 using quantum mechanics.

1.2 BONDING AND TYPES OF SOLIDS

1.2.1 Molecules and General Bonding Principles

When two atoms are brought together, the valence electrons interact with each other and with the neighbor's positively charged nucleus. The result of this interaction is often the formation of a bond between the two atoms, producing a molecule. The formation of a bond means that the energy of the system of two atoms together must be less than that of the two atoms separated, so that the molecule formation is energetically favorable, that is, more stable. The general principle of molecule formation is illustrated in Figure 1.2a, showing two atoms brought together from infinity. As the two atoms approach each other, the atoms exert attractive and repulsive forces on each other as a result of mutual electrostatic interactions. Initially, the attractive force F_A dominates over the repulsive force F_R . The net force F_N is the sum of the two,

$$F_N = F_A + F_R$$

and this is initially attractive, as indicated in Figure 1.2a.

The potential energy $E(r)$ of the two atoms can be found from⁴

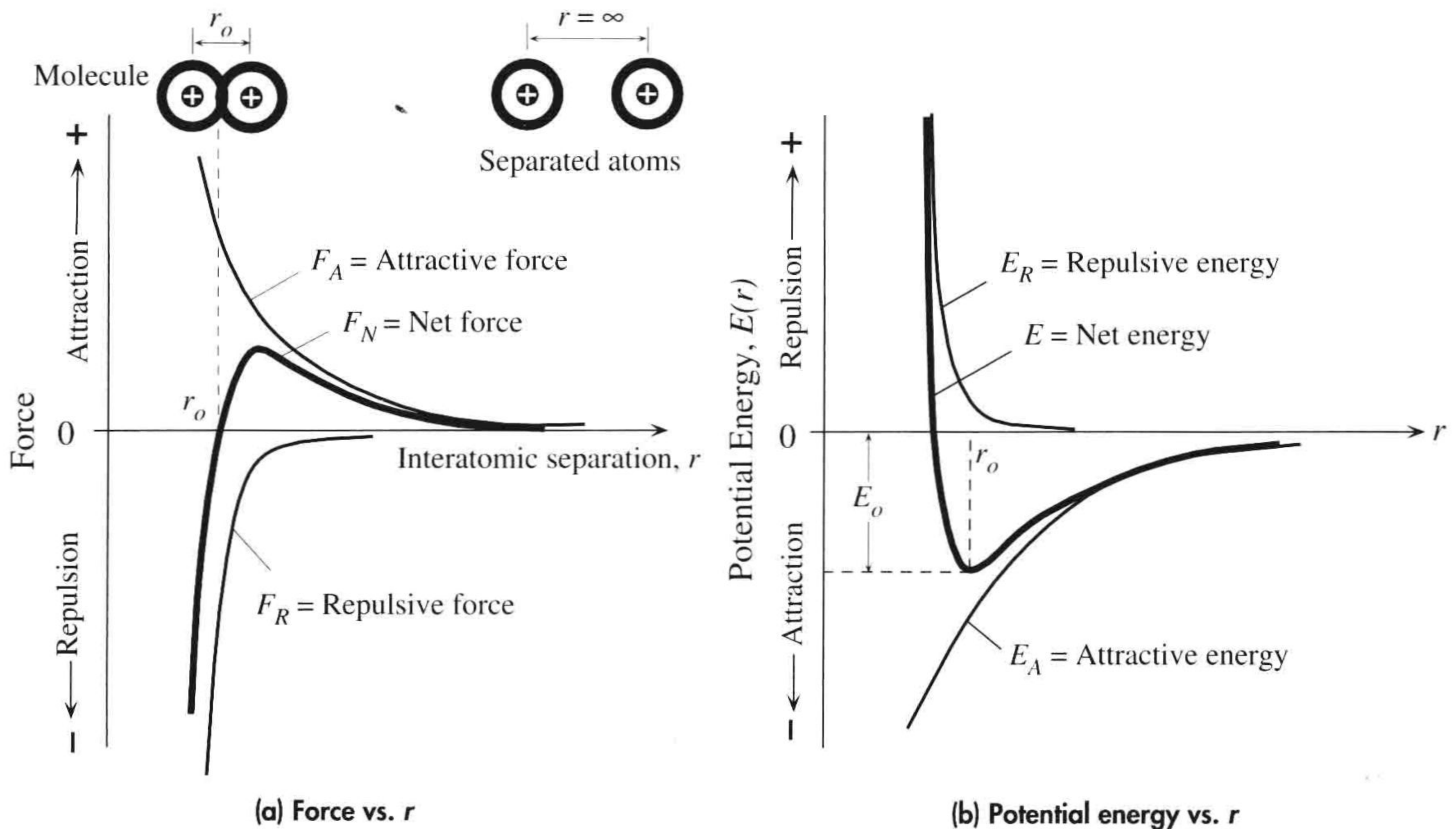


Figure 1.2 (a) Force versus interatomic separation and (b) potential energy versus interatomic separation.

⁴ Remember that the change dE in the PE is the work done against the force, $dE = Fdr$.