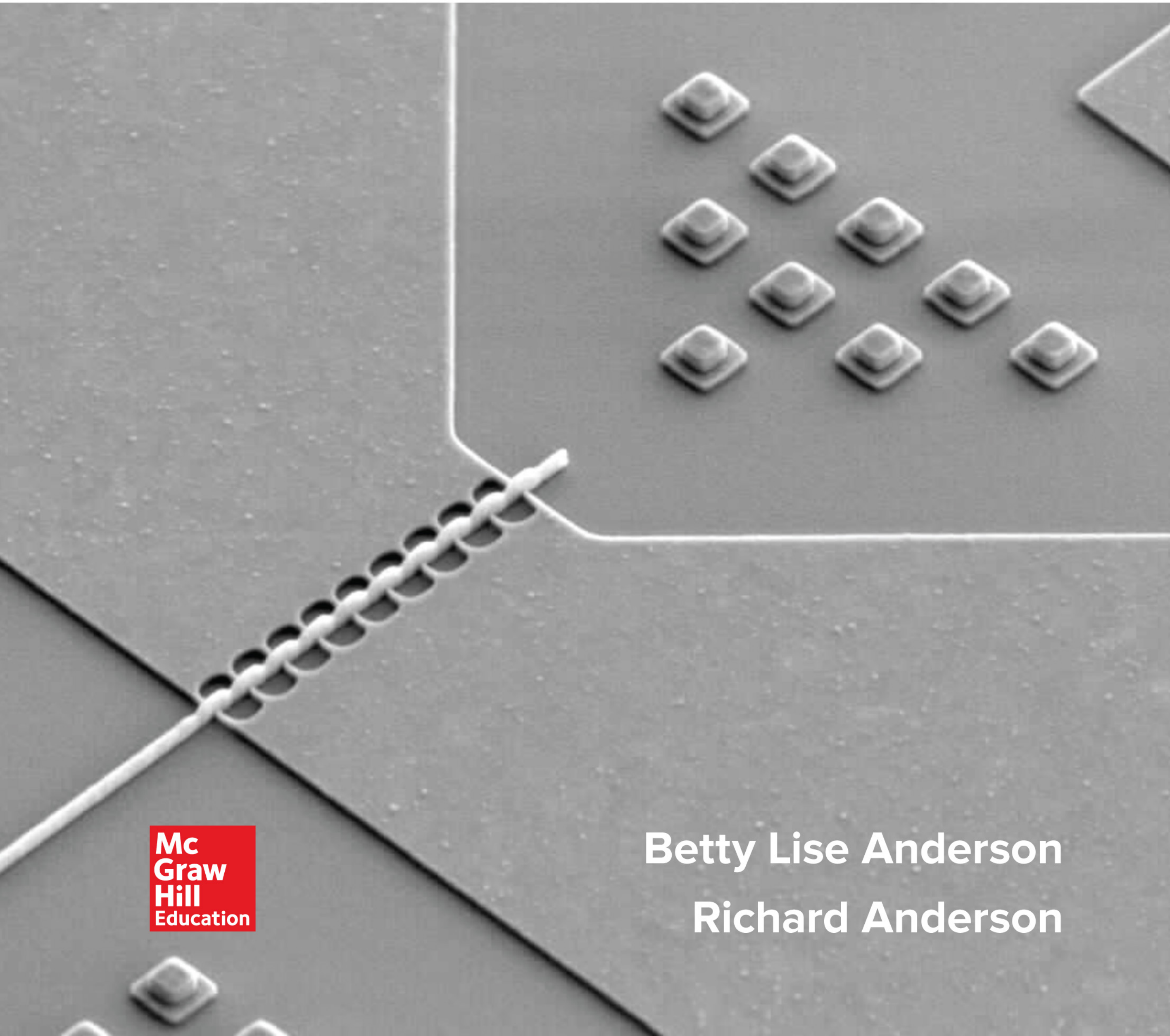
Fundamentals of SEMICONDUCTOR DEVICES

Second Edition



McGraw Hill Education

Betty Lise Anderson

Richard Anderson

Fundamentals of Semiconductor Devices

Second Edition

Betty Lise Anderson
The Ohio State University

Richard L. Anderson

Mc
Graw
Hill
Education

FUNDAMENTALS OF SEMICONDUCTOR DEVICES, SECOND EDITION

Published by McGraw-Hill Education, 2 Penn Plaza, New York, NY 10121.

This book is printed onacid-free paper.

1 2 3 4 5 6 7 8 9 LCR 21 20 19 18 17

ISBN 978–0–07–352956–1
MHID 0–07–352956–7

Senior Vice President, Products & Markets: *G. Scott Virkler*
Vice President, General Manager, Products & Markets: *Marty Lange*
Vice President, Content Design & Delivery: *Betsy Whalen*
Managing Director: *Thomas Timp*
Brand Manager: *Raghothaman Srinivasan/Thomas M. Scaife, Ph.D.*
Director, Product Development: *Rose Koos*
Product Developer: *Tina Bower*
Marketing Manager: *Shannon O’Donnell*
Director, Content Design & Delivery: *Linda Avenarius*
Program Manager: *Lora Neyens*
Content Project Manager: *Sherry Kane*
Buyer: *Laura Fuller*
Design: *Egzon Shaqiri*
Content Licensing Specialists: *Carrie Burger/Lorraine Buczek*
Cover Image: *Courtesy IMEC*
Compositor: *SPi Global*
Printer: *LSC Communications*

All credits appearing on page or at the end of the book are considered to be an extension of the copyright page.

Library of Congress Cataloging-in-Publication Data

Names: Anderson, Betty Lise, author. | Anderson, Richard L., author.
Title: Fundamentals of semiconductor devices / Betty Lise Anderson, The Ohio State University; Richard L. Anderson.
Description: Second edition. | Dubuque : McGraw-Hill Education, 2017.
Identifiers: LCCN 2016036979 | ISBN 9780073529561 (alk. paper)
Subjects: LCSH: Semiconductors. | Transistors.
Classification: LCC TK7871.85 A495 2017 | DDC 621.3815/2—dc23 LC record available at https://lccn.loc.gov/2016036979

www.mhhe.com

BRIEF CONTENTS

Mc Graw Hill Education
5011333

CONTENTS

PART 1

Materials 1

Chapter 1

Electron Energy and States in Semiconductors 3

Chapter 2

Homogeneous Semiconductors 48

Chapter 3

Current Flow in Homogeneous Semiconductors 113

Chapter 4

Nonhomogeneous Semiconductors 162

Supplement to Part 1

Introduction to Quantum Mechanics 180

PART 2

Diodes 223

Chapter 5

Prototype pn Homojunctions 227

Chapter 6

Additional Considerations for Diodes 302

Supplement to Part 2

Diodes 338

PART 3

Field-Effect Transistors 357

Chapter 7

The MOSFET 367

Chapter 8

Other Field-Effect Transistors 439

Supplement to Part 3

Additional Consideration for MOSFETs 493

PART 4

Bipolar Junction Transistors 539

Chapter 9

Bipolar Junction Transistors: Statics 544

Chapter 10

Time-Dependent Analysis of BJTS 590

Supplement to Part 4

Bipolar Devices 623

PART 5

Optoelectronic and Power Semiconductor Devices 643

Chapter 11

Optoelectronic Devices 644

Chapter **12**

Appendices

PREFACE

This is a textbook on the operating principles of semiconductor devices. It is appropriate for undergraduate (junior or senior) or beginning graduate students in electrical engineering, as well as students of computer engineering, physics, and materials science. It is also useful as a reference for practicing engineers and scientists who are involved with modern semiconductor devices.

Prerequisites are courses in chemistry and physics and in basic electric circuits, which are normally taken in the freshman and sophomore years.

The text is appropriate for a two- or three-semester course on semiconductor devices. However, it can be used for a one-semester course by eliminating some of the more advanced material and assigning some of the sections as read-only. The authors have attempted to organize the material so that some of the detail derivation sections can be skipped without affecting the comprehension of other sections.

This book is divided into five parts:

1. Materials
2. Diodes
3. Field-effect transistors
4. Bipolar transistors
5. Optoelectronic and power semiconductor devices

The first four parts are followed by “Supplements” that, while not required for an understanding of the basic principle of device operation, contain related material that may be assigned at the discretion of the instructor.

Part 1, “Materials,” contains four chapters and a Supplement. The first two chapters contain considerable review material from the prerequisite courses. This material is included because it is used extensively in later chapters to explain the principles of device operation. Depending on the detailed content on the prerequisite courses, much of the material in these chapters can be relegated to reading assignments.

The level of quantum mechanics to be covered in a course like this varies widely. In this book some basic concepts are included in the main chapters of Part 1. Those wishing to cover quantum mechanics in more detail will find more extensive material in the Supplement to Part 1.

The basic operating principles of large and small devices of a particular type (e.g., diodes, field-effect transistors, bipolar junction transistors, and photodetectors) are the same. However the relative importance of many of the parameters involved in device operation depends on the device dimensions. In this book the general behavior of devices of large dimensions is treated first. In each case, we treat “prototype” devices (such as step junctions and long channel field-effect transistors) from which the fundamental physics can be learned, and then we develop more realistic models considering second-order effects. These second-order effects can have significant influence on the electrical characteristics of modern small-geometry devices. The instructor can go into as much depth as desired or as time permits.

Topics treated that are typically omitted in undergraduate texts are:

- The differences between the electron and hole effective masses as used in density-of-states calculations and conductivity calculations.
- The differences in electron and hole mobilities (and thus diffusion coefficients) depending on whether they are majority carriers or minority carriers.
- The effects of doping gradients in the base of bipolar junction transistors (and/or the composition and heterojunction BJTs) on the current gain in switching speed.
- Band gap reduction in degenerate semiconductors. While this has little effect on the electrical characteristics of diodes or field-effect transistors, its effect in the emitter of bipolar junction transistors can reduce the current gain by orders of magnitude.
- The use of wide band-gap semiconductors (e.g., GaN and 4H-SiC) for use in high-power semiconductor devices.

While the major emphasis is on silicon and silicon-based devices, the operation of compound semiconductor devices, alloy devices (e.g., Si:Ge, AlGaAs) and heterojunction devices (junctions between semiconductors of different composition) are also considered because of the increased performance that is possible with *band-gap engineering*.

Fabrication, while an important part of semiconductor engineering, is often skipped in the interest of time. This material is introduced in Appendix C and can be assigned as read-only material if desired.

Supplemental topics are presented in a series of *Online Modules*. These modules, whose content is beyond that normally taught in a first course on semiconductor devices, contain material which supplements that of the book proper. For example, Online Module 7 describes some basic representative circuits utilizing CMOS devices. These Online Modules are available on the web for downloading.

ACKNOWLEDGMENTS

We would like to thank, first and foremost, our spouses Bill and Claire for their love, support, patience, and help. We are also grateful to the anonymous manuscript reviewers for their comments and suggestions, as well as staff at McGraw-Hill for all their help. We thank our students and their professors for valuable feedback on the first edition of the text. In particular, we thank Professor Gary Bernstein of Notre Dame University for his extensive comments and suggestions. We also wish to thank Cor Claeys and Rita Rooyackers of IMEC for scanning electron microscopy photographs of devices.

PART 1

Materials

INTRODUCTION

Semiconductors form the basis of most modern electronic systems (e.g., computers, communication networks, control systems). While there are applications for other materials in electronics (e.g., magnetic materials in hard drives), this book concentrates on electronic devices that are based on semiconductors.

Understanding the operation and design of semiconductor devices begins with an understanding of the materials involved. In Part 1 of this book, we investigate the behavior of electrons in materials, starting with the atoms themselves. Then we progress to electrons in crystalline semiconductors.

We will see that classical mechanics does not provide a complete picture of electron activity in solids. In principle, one should instead use quantum mechanics to predict the electrons' behavior, but the application of quantum mechanics is not as simple as the more familiar classical or Newtonian mechanics. We will therefore introduce pseudo-classical mechanics, which modifies familiar classical equations to account for some quantum mechanical effects.

Some basic quantum mechanical concepts important for the understanding of device operation are covered in Chapter 1. (A more detailed discussion is contained in Supplement to Part 1, found after Chapter 4.) In Chapter 2, we cover pseudo-classical mechanics, which allows us to predict the reaction of electrons to complicated fields, while using simple and intuitive pseudo-classical equations.

The use of pseudo-classical mechanics will also allow us to draw and use energy band diagrams. These diagrams are indispensable for understanding and predicting the motion of the electrons and holes, and thus the current in semiconductors.

In Chapter 3, we will see that conductivity of semiconductors is controlled by the number of charge carriers available to carry current. The charge carriers in semiconductors are electrons and holes. Their numbers are controlled by the concentrations of impurity elements that are intentionally added to the material. The carrier concentrations also depend on temperature and on whether light is shining on the sample.

It will emerge that there are two major forms of current in semiconductors, drift current and diffusion current. Drift current is caused by the presence of an electric field, whereas diffusion current arises when the carrier concentrations vary with position.

Chapter 4 covers nonhomogeneous semiconductor materials, in which the doping or the material composition itself may vary with position. These variations can lead to internal electric fields that can enhance device performance. Most modern semiconductor devices have regions of such nonhomogeneous materials.

The Supplement to Part 1 contains additional topics relevant to semiconductor materials, including a more detailed discussion of quantum mechanics and phonons.

We will start with electrons in atoms. ■

CHAPTER 1

Electron Energy and States in Semiconductors

1.1 INTRODUCTION AND PREVIEW

We begin our study of semiconductors with some fundamental physics of how electrons behave in matter. The ability to control the movement of electrons in solids is the basis of semiconductor device engineering. To understand the electronic properties of these devices, it is necessary to understand the electronic properties of the materials from which they are made and how those properties are affected by impurities (intentional and unintentional), temperature, applied voltages, device structures, and optical radiation.

Since solids are composed of atoms, we start by examining the electronic properties of atoms, and then extending those results to simple molecules and solids. In particular, the results for silicon (Si) and gallium arsenide (GaAs) are emphasized, two commonly used semiconductors in integrated circuits and semiconductor devices. Several other semiconductors and semiconductor alloys important in modern devices are also discussed.

As we investigate the atom, we'll be using quantum mechanics, a branch of science that is needed to accurately describe the behavior of very small objects such as atoms and electrons. We will see as we go along that quantum mechanics is based on the idea that energy can exist only in discrete packets, or quanta. The size of a quantum is so small that it doesn't affect one's results when one is computing the momentum or velocity of large objects such as automobiles or dust particles, but the quantum description is extremely important for electrons and atoms.

An understanding of quantum mechanics is not simple to obtain, and its use to calculate properties of more than a few systems in closed form is difficult. Fortunately, however, in semiconductors the behavior of electrons of interest can be determined by *pseudo-classical mechanics,* in which classical formulas such as Newton's laws and the Lorentz equation can be used, with the true electron mass replaced by an *effective mass.* As a result, in this section, a minimal discussion of quantum mechanics is presented. A somewhat greater discussion of quantum mechanics appropriate to some of the electronic processes in semiconductor devices is presented in the Supplement to Part 1, after Chapter 4.

The key to understanding semiconductors is to appreciate the physical interpretation of the mathematical results. Physical understanding is emphasized in this book.

1.2 A BRIEF HISTORY

In the early twentieth century, scientists were trying to develop models that would explain the results observed from such experiments as the scattering of X-rays, the photoelectric effect, and the emission and absorption spectra of atoms. In 1910, J. J. Thomson proposed a model of the atom in which a sphere of continuous positive charge is embedded with electrons, as shown in Figure 1.1a. Ernest Rutherford, in 1911, offered an improvement to the Thomson model: In the Rutherford model of the atomic structure, all of the positive charge and virtually all of the atom's mass were assumed to be concentrated in a small region in the center of the atom. This nucleus is often treated as a sphere with a radius on the order of 10^{-14} meters. The negatively charged electrons were assumed to orbit about the positively charged nucleus, much as planets orbit the sun or satellites orbit the earth.

In 1913, Neils Bohr assumed that the electrons in the Rutherford model of the atom orbited the nucleus in circles, as shown in Figure 1.1b. From this, he predicted that for the atom to be stable, the electrons could have only certain energies, or that the energies would be *quantized.* Energy and many other observables (properties that can be directly measured) are expressed in terms of Planck's constant. Planck's constant, *h,* has the value 6.63×10^{-34} joule–seconds.

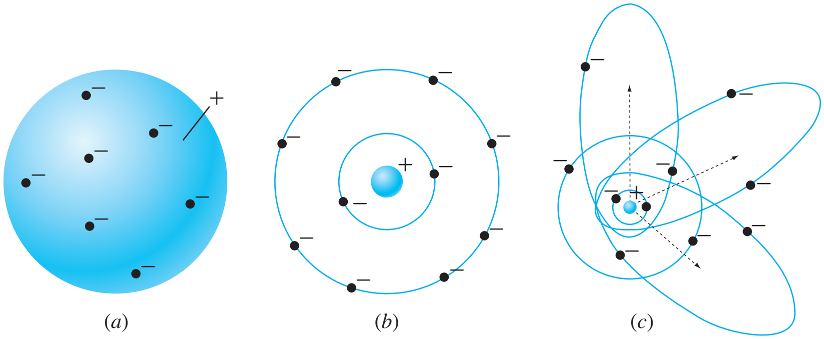


Figure 1.1 (a) The Thomson model of an atom, in which the positive charge is uniformly distributed in a sphere and the electrons are considered to be negative point charges embedded in it; (b) the Bohr model, in which the positive charge is concentrated in a small nucleus and the electrons orbit in circles; (c) the Wilson-Sommerfeld model, which is similar to the Bohr model except that it allows for elliptical orbits.

The energies Bohr predicted for electrons in atoms were in excellent agreement with the experimental results obtained from spectroscopic data.

In 1916, Wilson and Sommerfeld generalized the Bohr model to apply it to any physical system in which a particle's motion is periodic with time. This modification allows for the possibility of elliptical orbits, as shown in Figure 1.1c.

1.3 APPLICATION TO THE HYDROGEN ATOM

In this section, we briefly review the Bohr model of the hydrogen atom. The hydrogen atom is emphasized because *hydrogen-like impurities* are important in semiconductor devices, and these impurities can be treated in a manner analogous to the Bohr model. In the Supplement to Part 1, we will compare these results to those obtained using quantum mechanics as represented by Schrödinger's equation.

1.3.1 THE BOHR MODEL FOR THE HYDROGEN ATOM

We start with the Bohr model, in which the electrons revolve around the nucleus in circular paths. Because the mass of the nucleus is 1.67×10^{-27} kg, 1830 times that of the electron, the nucleus is considered to be fixed in space.

We consider as an example the neutral hydrogen atom, which has one orbiting electron, and we treat the electron and nucleus both as point charges. The coulomb force between two particles with charges Q_1 and Q_2 is

$$F = \frac{Q_1 Q_2}{4\pi\varepsilon_0 r^2} = \frac{-q^2}{4\pi\varepsilon_0 r^2} \tag{1.1}$$

where r is the distance between the two charges and $\varepsilon_0 = 8.85 \times 10^{-12}$ farads/meter is the permittivity of free space (because there is only free space between the nucleus and the electron). The expression at the far right-hand side of Equation (1.1) is obtained by recognizing that the hydrogen nucleus has only one proton, so Q_1 is equal to $+q = 1.602 \times 10^{-19}$ Coulombs, the elemental charge, and the charge of the electron Q_2 is equal to $-q$. The resulting negative sign in Equation (1.1) indicates that the force is attractive.

We now have an expression for the attractive (centripetal) force between the two particles, and we recall from classical mechanics that the force F on a particle is equal to minus the gradient of the potential energy, or

$$F = -\nabla E_p = -\frac{dE_P}{dr} \tag{1.2}$$

In the last expression, the gradient is taken in the r direction, and E_P is the potential energy of the electron at position r. Equation (1.2) with the aid of (1.1) can be rewritten as

$$dE_P = dE_P(r) = -F dr = \frac{q^2\, dr}{4\pi\varepsilon_0 r^2} \tag{1.3}$$

One can integrate both sides to obtain E_P, but there will be a constant of integration. The actual value of the potential energy is arbitrary (as is the choice of the constant), since the value of the potential energy depends entirely on one's choice of reference. We can choose a convenient reference by noting that the coulomb force at infinite distance is zero. It makes sense for this case, then, to choose $r = \infty$ as a reference point, so we define the potential energy at $r = \infty$ as the *vacuum level,* E_{vac}:

$$E_P(r = \infty) = E_{\text{vac}} \tag{1.4}$$

This is the energy required to free the electron from the influence of the nucleus, essentially by moving the electron infinitely far away from it. If the electron is infinitely far from the nucleus, it cannot really be considered part of the atom—it is now a free electron in vacuum.

Now we can solve Equation (1.3) for a given value of r:

$$\int_{E_P}^{E_{\text{vac}}} dE_P = \int_{r}^{\infty} \frac{q^2\,dr}{4\pi\varepsilon_0 r^2} \tag{1.5}$$

where E_P is the electron potential energy at some distance r from the nucleus. Integrating both sides and rearranging, we obtain

$$E_P = E_{\text{vac}} - \frac{q^2}{4\pi\varepsilon_0 r} \tag{1.6}$$

Figure 1.2 shows a plot of the r dependence of E_P. From Equation (1.1), and since the force is equal to minus the gradient (slope) of the potential energy, we see that the force on the electron is directed toward the nucleus, or the coulomb force is centripetal. Since the nucleus is considered to be a point charge, E_P approaches negative infinity as r approaches zero. Since the radius of the nucleus is on the order of 10^{-14} m, however, and the radius of the smallest electron orbit is on the order of 10^{-10} m, the potential energy reaches a minimum near $r = 0$.

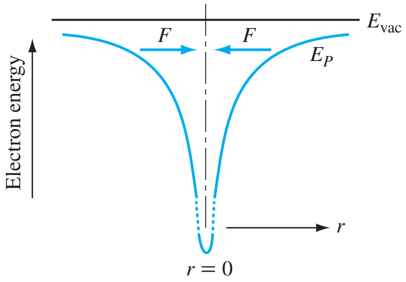


Figure 1.2 Potential energy diagram for an electron in the vicinity of a single positive point charge. The electron is considered to be a point charge.

Since the electron is revolving in a circle of radius *r* around the nucleus, we know from Newtonian mechanics that its centrifugal force is equal to

$$F = \frac{m\upsilon^2}{r} \tag{1.7}$$

For the atom to be stable, the net force on the electron must be zero. Equating our previous expression for the centripetal force due to the coulomb attraction [Equation (1.1)] to the centrifugal force [Equation (1.7)], we can write

$$\frac{m\upsilon^2}{r} - \frac{q^2}{4\pi\varepsilon_0 r^2} = 0 \tag{1.8}$$

Bohr also postulated that the integral of the angular momentum around one complete orbit is an integer multiple of Planck's constant *h:*

$$\oint P_\theta d\theta = \int_0^{2\pi} m\upsilon r d\theta = nh \tag{1.9}$$

where *n* is an integer. Since the orbit is assumed circular in the Bohr model, *r* is a constant, and so are the potential energy E_P and the speed υ. Therefore, the integral becomes

$$2\pi m r\upsilon = nh \tag{1.10}$$

There is a solution for each integer value of *n,* so we write

$$m\upsilon_n r_n = n\frac{h}{2\pi} = n\hbar \tag{1.11}$$

Here we have introduced a new symbol; it turns out that engineers and physicists (and now you) use the quantity $h/2\pi$ so much that there is a special character for it, $\hbar$, pronounced "h-bar." The subscripts *n* in Equation (1.11) indicate the particular orbital radius or speed associated with a specific quantum number *n.*

If we simultaneously solve Equations (1.8) and (1.11), we can derive an expression for the *Bohr radius of the nth state,* where by "state" we mean the properties associated with a particular value of *n:*

$$r_n = \frac{4\pi\varepsilon_0 n^2\hbar^2}{mq^2} \tag{1.12}$$

and the speed of the electron in that particular state is

$$\upsilon_n = \frac{q^2}{4\pi\varepsilon_0 n\hbar} \tag{1.13}$$

Our primary goal, however, is to find the energies associated with these states. We know that the total energy of a system is equal to the kinetic energy plus the potential energy. The kinetic energy of the *n*th energy level is

$$E_{K_n} = \frac{1}{2}m\upsilon_n^2 = \frac{mq^4}{2(4\pi\varepsilon_0)^2 n^2\hbar^2} \tag{1.14}$$

For the nth energy level, we can find r_n from Equation (1.12) and use that in Equation (1.6) to write for the potential energy

$$E_{Pn} = E_{\text{vac}} - \frac{mq^4}{(4\pi\varepsilon_0)^2 n^2 \hbar^2} \tag{1.15}$$

Thus, the total energy E_n is

$$E_n = E_{Kn} + E_{Pn} = E_{\text{vac}} - \frac{mq^4}{2(4\pi\varepsilon_0)^2 n^2 \hbar^2} \tag{1.16}$$

We say that the energy is *quantized.* It can have only discrete values associated with the quantum number n. We note that $n = 1$ refers to the smallest radius and energy of the electron in the Bohr model, $n = 2$, the next larger values, etc.

EXAMPLE 1.1

Find the energies and radii for the first four orbits in the hydrogen atom.

■ Solution

$$\begin{aligned}
E_n &= E_{\text{vac}} - \frac{mq^4}{2(4\pi\varepsilon_0)^2 n^2 \hbar^2} \\
&= E_{\text{vac}} - \frac{(9.11\times10^{-31}\,\text{kg})(1.60\times10^{-19}\,\text{C})^4}{(2)(4)^2(3.1416)^2(8.85\times10^{-12}\,\text{F/m})^2(1.05\times10^{-34}\,\text{J}\cdot\text{s})^2}\left(\frac{1}{n}\right)^2 \\
E_n &= E_{\text{vac}} - \left(\frac{1}{n}\right)^2(2.18\times10^{-18}\,\text{J}) \\
&= E_{\text{vac}} - \left(\frac{1}{n}\right)^2(13.6\,\text{eV})
\end{aligned} \tag{1.17}$$

Here a new unit of energy is introduced, the *electron volt* (eV). The electron volt is defined as the amount of energy acquired by an electron when it is accelerated through 1 volt of electric potential. To convert between SI (International System) units (joules) and electron volts, use

$$\boxed{1\ \text{eV} = 1.60\times10^{-19}\ \text{joules}}$$

Electron volts are *not* SI units, and therefore they must be used with care in calculations.

The Bohr radii can be calculated from Equation (1.12):

$$\begin{aligned}
r_n &= \frac{4\pi\varepsilon_0 n^2\hbar^2}{mq^2} = \frac{(4)(3.1416)(8.85\times10^{-12}\,\text{F/m})(1.05\times10^{-34}\,\text{J}\cdot\text{s})^2}{(9.11\times10^{-31}\,\text{kg})(1.60\times10^{-19}\,\text{C})^2}\times n^2 \\
r_n &= 0.0526\,n^2\,\text{nm}
\end{aligned} \tag{1.18}$$

The energies and Bohr radii of the first four energy levels are given in Table 1.1. These energies and radii are plotted in Figures 1.3 and 1.4, respectively.

Table 1.1 The first four Bohr energies and orbital radii for the hydrogen atom

E_n	r_n
$E_1 = E_{\text{vac}} - 13.6\text{ eV}$	$r_1 = 0.0526\text{ nm}$
$E_2 = E_{\text{vac}} - 3.40\text{ eV}$	$r_2 = 0.212\text{ nm}$
$E_3 = E_{\text{vac}} - 1.51\text{ eV}$	$r_3 = 0.477\text{ nm}$
$E_4 = E_{\text{vac}} - 0.850\text{ eV}$	$r_4 = 0.848\text{ nm}$

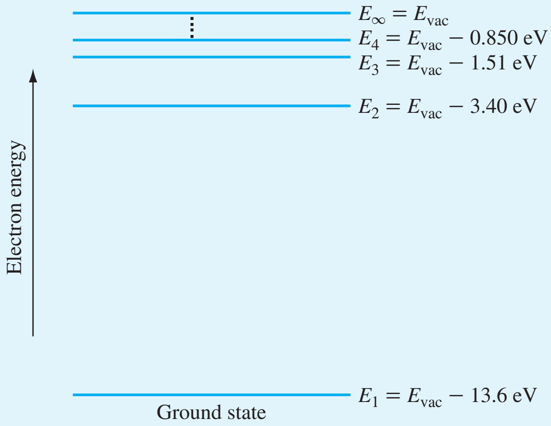


Figure 1.3 Allowed energies in the hydrogen atom. Higher energies occur increasingly close to each other, approaching the vacuum level.

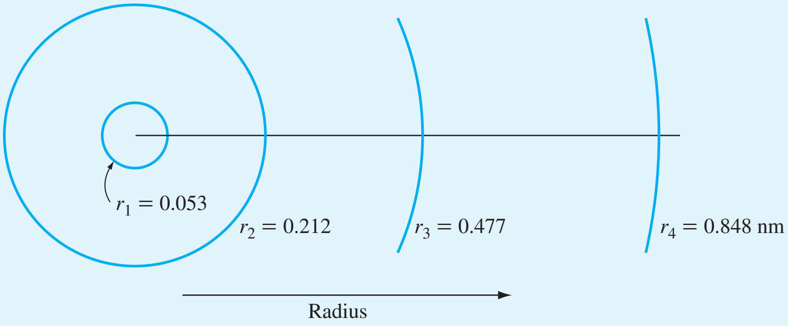


Figure 1.4 Radii of the first four electronic orbits of the hydrogen atom, according to the Bohr model.