TRANSISTORS

Dennis Le Croissette

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Transistors

by

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Preface

The aim of this book is to present and explain the basic principles of semiconductor electronics as they apply to junction transistors. The introductory approach makes it suitable for use as an undergraduate text in electrical engineering. It will also be helpful to engineers in industry who require a knowledge of transistors.

The fundamentals of semiconductor devices are introduced here from a physical viewpoint. In my opinion, this is the best preparation for later work in electronic circuitry, where device limitations must be considered. Moreover, vacuum tube

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electronics is relatively easy to understand after these concepts have been developed. This opinion is supported by experience at Drexel Institute of Technology where part of this material was used as the first course in electronics.

Part 1 of this book is concerned with the flow of electrons and holes in semiconducting materials, leading to an understanding of current flow in *p-n* junctions and transistors.

In Part 2, the "black box" concept of the transistor is developed. Analysis is restricted to low frequency operation of the device, and hybrid (or *h*) parameter representation is used. Direct-current operation of the transistor is also considered.

Part 3 consists mainly of an analysis of the high frequency and pulse operation of the transistor. The hybrid-π circuit is derived and used to determine the high frequency response of the common emitter stage. Pulse operation is described from the charge storage point of view. In conclusion, the tunnel diode is discussed.

It is apparent that this book, designed primarily for engineers, cannot derive all the physical relationships necessary for an analysis of the transistor. The references at the end of each chapter assist the reader to find the derivations he requires.

I feel strongly that this textbook is not suitable for a course oriented towards solving numerical problems. Therefore, many descriptive questions have been given to encourage students to review and rephrase the material.

I would like to acknowledge the assistance of John Yarwood of London, England and Eugene J. Rosenbaum of Philadelphia, Pa. who read part of the manuscript while it was in preparation. My former colleagues at Drexel Institute of Technology have made a number of helpful comments. I am also grateful to Albert F. Fuchs for contributing many of the problems and to Mrs. Noreen J. Reyes for typing most of the manuscript.

DENNIS LE CROISSETTE

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PART 1

The Motion of Electrons and Holes in Semiconducting Materials

1

Electrical Conduction in Semiconductors

When the vacuum tube was the only practicable electronic amplifier, the subject of electronics was predominantly concerned with the flow of electrons in a vacuum or in a gas at low pressure. In the past twenty years, however, considerable attention has been focused on the conduction of electricity in solid materials. Research in solid-state electronics was accelerated by the development of the transistor in 1948. Since that date, a study of the processes governing current flow in semiconductors has been essential for an understanding of electronics.

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This chapter begins with a review of the basic atomic properties of matter leading to the energy band representation of insulators, conductors, and semiconductors. Later in this chapter, the fundamental concept of hole and electron conduction in a semiconductor is developed, and recombination between holes and electrons is briefly discussed.

1–1 Introduction

In the past, solid materials were divided into two main groups according to their electrical resistivity: *conductors* and *insulators.* Conductors were loosely defined as having resistivities less than about 10^{-3} ohm cm, and this group of materials included all the metals. Insulators were considered to include substances with resistivities higher than 10^{8} ohm cm and in this category were ebonite, glass, mica, etc. Materials having a resistivity between these two values were known, but it was often difficult to measure their resistivity accurately since different specimens of the same substance gave different results. Such materials are called *semiconductors*, and an explanation of their electrical properties will be given later in this chapter. The elements *germanium* and *silicon* are the two most used semiconductors, and the electrical properties of these materials are responsible for the operation of transistors and other semiconducting devices.

The transistor is the most important of the *solid-state devices.* In a solid, the passage of current is determined by the binding forces which act between electrons and the positively charged atomic nuclei. Therefore, the emphasis in beginning this study of modern electronic theory will be placed upon an understanding of the physical properties of the atom.

1–2 Simple Theory of the Hydrogen Atom

Rutherford first proposed an atomic model of the type shown in Fig. 1–1. In this diagram, an electron is shown revolving in a circular orbit around a positively charged nucleus. In the case of hydrogen, it is known that the positive charge in the nucleus is numerically equal to the charge on the

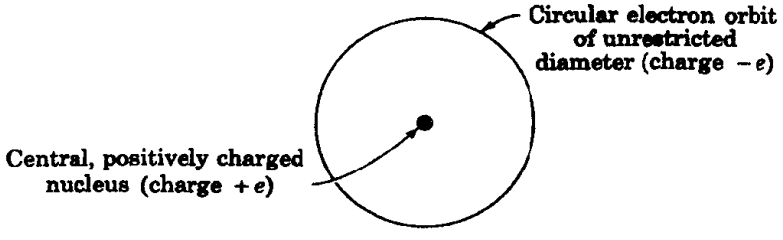

FIG. 1–1. Simple picture of the hydrogen atom.

electron (e). Coulomb's law states that the force of attraction between these two charges is

$$\frac{e^2}{4\pi\varepsilon_0 r^2}$$

where r is the radius of the orbit in meters, and ε_0 is the permittivity of a vacuum.

If the electron is revolving with velocity v in meters per second, the radial force necessary to restrain it in a circular orbit of radius r is mv^2/r. Hence,

$$\frac{e^2}{4\pi\varepsilon_0 r^2} = \frac{mv^2}{r} \tag{1–1}$$

Equation (1–1) is seen to be a result of the application of the classical laws of mechanics and electrostatics. It does not place any restriction on the radius of the electron orbit, and it is inadequate to explain why the electron remains in equilibrium in its path around the nucleus. Any change in the radius of the orbit will be accompanied by a change in the energy of the system [see Eq. (1–10)]. According to this theory, if the electron moves to a new orbit closer to the central nucleus, the energy of the system falls, and the excess energy is radiated out into space. This process will be repeated as time goes on and eventually the electron will fall into the nucleus. It is clear that Eq. (1–1) alone is incapable of explaining the motion of the electron around the nucleus.

An additional discrepancy between this simple theory and experiment is that this model does not explain the mechanism of the emission and absorption of radiation which takes place in a gas. Studies of the emission and absorption spectra of various gases show that certain frequencies appear which are characteristic of the gas. It is concluded, therefore, that definite energy levels are possible in the atom and that emission or absorption of radiation occurs when electrons move from one energy level to another. Classical theory is unable to explain this phenomenon since it does not indicate the presence of definite electron energy levels in the atom.

1–3 Bohr's Theory of the Hydrogen Atom

In 1913, Bohr suggested that these difficulties could be overcome by a direct application of Planck's *quantum theory*. The idea of a *quantum of energy* is fundamental to modern electronic theory since it is concerned with the emission and absorption of energy on an atomic scale. This was one of the first of many successful applications of quantum theory in the solution of atomic problems and led to the later and more exact theory of the atom.

The quantum theory states that all energy is emitted and absorbed in the form of multiples of a unit called the *quantum*. Unlike the more familiar

units of energy, the energy in each quantum is a function of frequency and is given by

$$E = h\nu \tag{1-2}$$

where E is the energy of one quantum, in joules; h is Planck's constant, 6.62×10^{-34} joule sec; and ν is the frequency of radiation, in cycles per second. The amount of energy in a quantum is very small so that the emission and absorption of energy in experiments in ordinary mechanics are not affected. However, many atomic phenomena are governed by laws which may be deduced from the quantum theory.

Bohr applied this theory to show that it was possible to restrict the orbital radii to certain discrete values. He imposed a quantum condition on the value of the angular momentum in an orbit and showed that this was necessary for the establishment of equations which fitted the experimental facts. When the magnitude of any quantity is restricted to multiples of a small unit (such as a quantum of energy), the quantity is said to be "quantized." The quantization carried out by Bohr [Eq. (1–5)] was later shown to be the restriction of angular momentum to multiples of a small unit.

Bohr's model of the atom is based upon two assumptions.

1. The radius of the orbit is limited to certain fixed values, and no emission or absorption of energy takes place while the electron remains in one of the permitted orbits.
2. When the electron jumps from an orbit of one allowed radius to another, emission or absorption of a quantum of energy occurs. The frequency of radiation can be found from

$$h\nu = E_2 - E_1 \tag{1-3}$$

where E_2 and E_1 are the energy levels of the two electron orbits.

Assuming that the electron revolves in a circle around the nucleus, its angular momentum is

$$mvr \tag{1-4}$$

The quantum condition imposed by Bohr on the angular momentum was that

$$mvr = \frac{nh}{2\pi} \tag{1-5}$$

where n is a positive integer known as the principal quantum number. This number determines the energy of the orbit.

Eliminating v from Eqs. (1–1) and (1–5) gives

$$r_n = \frac{n^2h^2\varepsilon_0}{\pi me^2} \tag{1-6}$$

where r_n is the radius of the nth orbit.

Inserting the known values of the physical constants, h, ε_0, m, and e (see Appendix) in Eq. (1–6) and taking $n = 1$

$$\begin{aligned} r_1 &= 0.529 \times 10^{-10} \text{ meter} \\ &= 0.529 \text{ A} \quad \text{(Angstrom units)} \end{aligned} \tag{1–7}$$

The value of r_1 for the hydrogen atom is known as the Bohr radius, r_B. It is of the same order as the effective radius of the atom found from kinetic theory. From Eq. (1–6),

$$\begin{aligned} r_1 &= r_B \\ r_2 &= 4r_B \\ r_3 &= 9r_B \\ r_4 &= 16r_B \quad \text{etc.} \end{aligned} \tag{1–8}$$

In this way, Bohr suggested that the allowed radii that the electron orbits could take were in the ratio $1^2, 2^2, 3^2, 4^2, \ldots$. This is shown in Fig. 1–2.

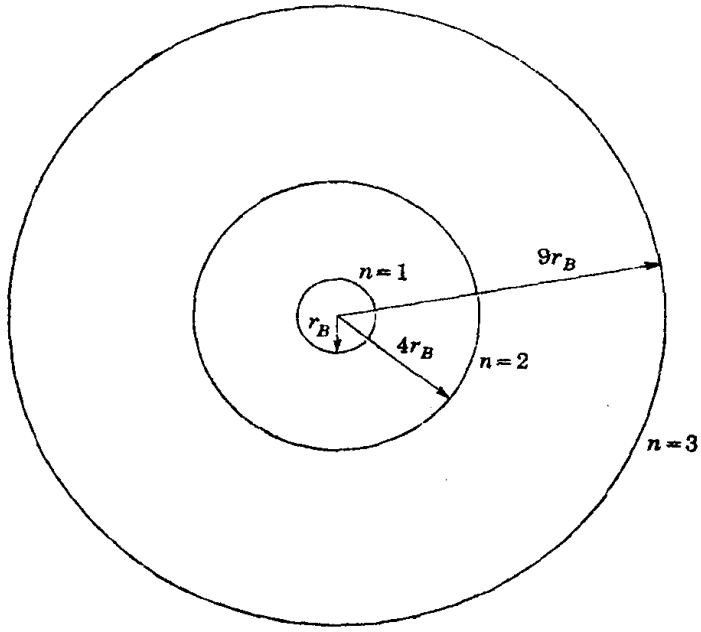

FIG. 1–2. Bohr theory of the hydrogen atom showing the first three electron orbits.

1–4 Energy of the Electron Orbits of the Hydrogen Atom

The kinetic energy of an electron revolving in an orbit with velocity v is $\frac{1}{2}mv^2$. From Eq. (1–1),

$$\text{K.E.} = \frac{e^2}{8\pi\varepsilon_0 r_n} \tag{1–9}$$

The potential energy of this electron is the product of the electric potential at the point and the charge on the electron.

$$\text{P.E.} = \frac{e}{4\pi\varepsilon_0 r_n}(-e) = \frac{-e^2}{4\pi\varepsilon_0 r_n} \tag{1-10}$$

Note that the potential energy is negative and numerically is twice the value of the kinetic energy. In electrical systems, the potential energy at a point may be negative without any special significance being attached to the fact. Electrical potential is defined as the work done against the field in bringing a unit positive charge from infinity up to the point; the electrical

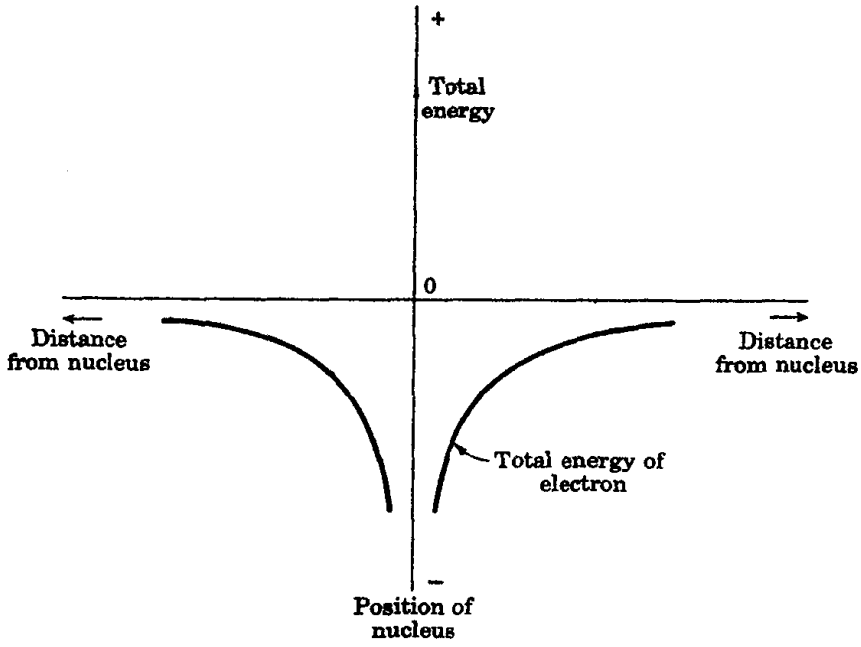

FIG. 1–3. Plot of the total energy of an electron close to the hydrogen nucleus.

potential at a point near a negative charge is, therefore, negative in sign. This definition means that the potential energy of the ionized atom is taken to be zero (see Fig. 1–3).

The total energy of the electron in orbit of radius r_n is

$$\text{K.E.} + \text{P.E.} = -\frac{e^2}{8\pi\varepsilon_0 r_n} \tag{1-11}$$

Substituting for r_n from Eq. (1–6),

$$\text{Total energy, } E_n = -\frac{me^4}{8n^2h^2\varepsilon_0^2} \tag{1-12}$$

where E_n is the energy of the nth orbital state (radius r_n).

The inner orbit where $n = 1$ has the lowest (i.e., the most negative) energy and is known as the *ground state*. In the hydrogen atom, the electron will remain in this state unless it is disturbed by outside influences.

1-5 Transitions between the Orbits

The simple case of hydrogen serves as a useful starting point towards understanding the way in which the absorption and emission of energy take place

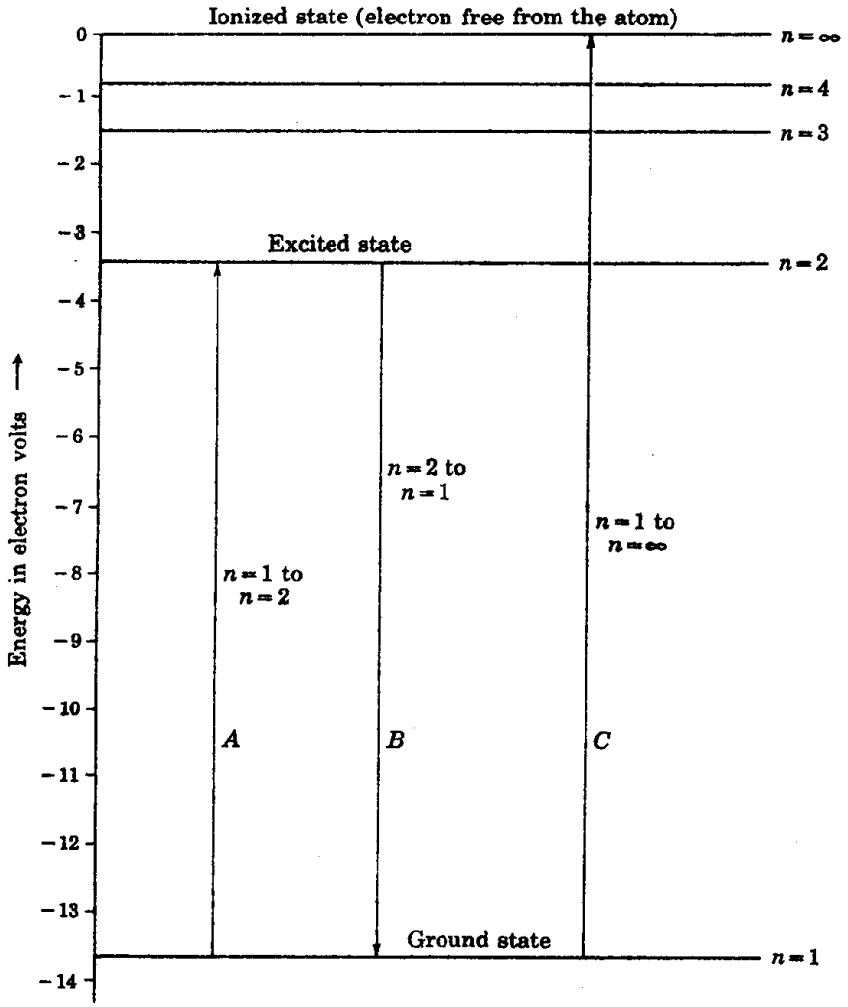

FIG. 1-4. Energy level representation for the Bohr theory of the hydrogen atom.

in an atomic system. The single orbital electron of a hydrogen atom can be removed from the ground state $n = 1$ and brought into the state $n = 2$ if electromagnetic radiation of a certain frequency is incident on the atom. To move the electron from one orbit to another requires a quantum of energy

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