ELECTRONIC CIRCUITS

Digital and Analog

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Preface

This book is an introduction to electronics. Its objective is to present in a clear, organized, and logical manner the fundamentals essential to electronic circuit design and analysis, both analog and digital. Although *Electronic Circuits* is planned for use in a junior-level course in electronics, it will also be useful to practicing engineers who wish to keep abreast of developments in this field. The reader is expected to have a knowledge of elementary calculus and electric network theory, as well as enthusiasm for learning about an exciting field of engineering.

It is interesting to note that in a span of only a few years several logic families have been introduced, become very popular, and then faded. Examples are diode-transistor logic, resistor-transistor logic, and standard transistor-transistor logic. Today new logic systems are being developed, and some have considerable potential for increasing substantially the capabilities of electronic systems. In view of this it is imperative that young electronics engineers be educated so that they acquire a firm grasp of fundamentals that apply not only to current technologies but also to technologies that surely will emerge.

The heart of semiconductor electronics is the bipolar junction transistor. Bipolar transistors employed in logic gates operate not only in the active region normally encountered in linear circuitry but also in the saturation, inverse, and cutoff regions. The engineer who is to design circuits intelligently with these gates must understand their operation and their characteristics. This requires a knowledge of the physical mechanisms occurring within the transistor in each of the four operating modes. Engineers must be equally familiar with the field-effect transistor, which is also of immense importance. Accordingly, the four chapters that constitute Part 1 of the book examine these devices carefully, along with films, hybrids, and integrated circuit technology.

The seven chapters of Part 2 treat digital circuitry. This material is placed ahead of that on analog circuits because electronics today is predominantly digital and becoming even more so as time progresses. Analog circuits are presented in Part 3, with operational amplifiers introduced early. OP AMP circuits and applications are emphasized throughout the analog section.

A wide range of topics is presented in this book, and more material is included than would normally be covered in a one-year introductory course. However, the book is organized so that it can be used in courses confined to analog circuits, or digital circuits, or portions of both. In order to provide flexibility, special care has been exercised in the preparation of Part 3 so that it can directly follow Part 1.

The book is oriented toward devices and technologies that are important today, with special emphasis given to circuit design. MOSFET logic gates are carefully examined, including PMOS, NMOS, CMOS, and dynamic MOS networks. The new logic I^2L is analyzed in some detail. Throughout the book the orientation is strongly toward the integrated circuit. Devices and circuits are investigated by means of numerical analyses, and numbers are selected to correspond closely with practical integrated-circuit values.

In 1977 a discernable trend is developing in industry to switch to MOSFET technology at the expense of bipolar technology. MOSFET circuits are becoming popular and common. Three chapters (3, 8, and 17) are wholly devoted to field-effect electronics, and numerous applications of FET digital and analog networks are presented in these and other chapters. It is well recognized that the bipolar junction transistor is superior to FET devices in gain and speed. It remains dominant in analog circuitry, and bipolar digital technology is making a considerable resurgence as newer types of integrated circuits become available. Thus extensive coverage of both bipolar and field-effect devices and circuits is provided, including networks containing both types of active devices.

The end-of-chapter problems are an integral part of the book. Each problem has been carefully prepared either to illustrate an important principle or to present new and meaningful material. The problems are arranged by section number and are closely related to the associated section. Students are strongly encouraged to work as many of them as possible, and they should endeavor to absorb the full significance of the results.

Although preparation of this book has required many hours of diligent work, it has been an enjoyable experience. My greatest hope is that the book will contribute substantially to the progress of engineering education.

Blacksburg, Va.
1977

Charles A. Holt

Suggestions for Course Organization

Electronic Circuits has been designed for flexibility. The contents of Part 2 on digital circuits are not in any way prerequisite to those of Part 3. Thus there are various ways in which the material may be organized in an introductory course. Individual instructors will undoubtedly develop their own course organization, after considering prerequisite material. The comments in this section may be useful as guidelines.

All introductory courses should begin with Chapters 1 and 2, which examine the bipolar junction transistor. However, this material can be covered fairly quickly. When developments based on the concepts of Chapters 1 and 2 appear in later chapters, the student should be encouraged to review these concepts. The material of Chapter 3 on Field Effect Transistors need not be covered before Chapter 8 of Part 2 and Chapter 17 of Part 3. Chapter 4 is a one-lesson reading assignment on integrated-circuit technology.

For a general course of broad scope *the contents of Parts 2 and 3 can be interspersed as desired.* One suggestion is to study combinational logic, transistor switching, and BJT logic gates in Chapters 5, 6, and 7 and then advance to Chapters 12 through 16 on BJT models, basic amplifier configurations, OP AMPs, bias circuits, and audio power amplifiers. After this, the program might return to the digital section. A first course designed to emphasize digital circuits should follow the material in the order presented.

In some cases it may be desirable to lead the student rather quickly into the design and analysis of analog circuits. This can be accomplished by proceeding *from Chapter 2 directly to Chapter 12*, which treats incremental models. The first two sections of Chapter 12 can be covered quickly. After studying the basic CE, CC, and CB configurations in Chapter 13, the student encounters the operational amplifier in Chapter 14, along with numerous important and interesting applications. Upon completion of Chapter 14 it might be well to return to the Combinational Logic Design of Chapter 5. Many students are quite interested in OP AMPs and also digital networks, and the approach suggested here is attractive because of its appeal to these students.

It is believed the book may prove beneficial in certain specialized courses. For example, the contents of Chapters 18 through 24 are appropriate for an advanced course emphasizing amplifier design that uses feedback techniques, along with various applications of linear integrated circuits. A course on field-effect electronics can be organized around Chapters 3, 8, and 17, with additional topics selected from Chapters 9, 10, 11, and 18.

C. A. H.

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C. A. H.

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PART ONE
TRANSISTOR FUNDAMENTALS AND INTEGRATED CIRCUIT TECHNOLOGY

Chapter One
The PN Junction

This book develops, in a logical manner, the basic theories and principles necessary for the intelligent design and proper utilization of electronic circuits. This necessitates a brief study of *device physics*, which treats the internal conduction processes of the various devices that are important to us, leading to the development of precise relationships between the terminal voltages and currents. *Solid-state physics*, which explains the conduction processes from the viewpoint of the band theory of solids, based on quantum mechanics, is of the greatest importance to many electronics engineers, particularly those developing new devices. However, it is perhaps best studied *after* an introductory course on electronic circuits.

In the development of device physics it is necessary to present without proof a few principles and laws from the realm of solid-state physics. These will be referred to as *postulates*, and they serve as the foundation that is required for the study of transistors.

Semiconductor physics is applied here to the PN junction, and in the following two chapters it is applied to both the bipolar junction transistor (BJT) and the field-effect transistor (FET). The analysis and design of electronics circuits is the subject of most of the remainder of the book.

Units used are those of the *Système International* (*SI*). The basic SI units are the *meter*, *kilogram*, *second*, *ampere*, and *kelvin*.

1-1. SEMICONDUCTOR CHARGE CARRIERS

A crystal is a solid whose atoms are arranged in a symmetrical, periodic array. Metals, semiconductors, and many insulators are crystalline. At normal temperatures semiconductors are characterized by conductivities that are intermediate between those of metals and those of good insulators. Of special interest to us are the semiconductors silicon and germanium.

Postulate 1. *A semiconductor has two types of charge carriers—the hole with charge* +q, *and the free electron with charge* −q, *with* $q = 1.6 \times 10^{-19}$ C. The hole density in holes per cubic meter is designated by the symbol *p*, for positive. The free-electron density is designated by the symbol *n*, for negative. Holes and free electrons move through a crystal in a random manner at high speeds, of the order of 10^5 m/s, encountering frequent collisions with the atoms. An applied electric field exerts forces on these charge carriers, causing them to acquire small drift velocities, resulting in hole and electron *drift currents* in the direction of the applied field.

Postulate 2. *A semiconductor may have two types of immobile ionized impurity atoms—the donor ion with charge* +q, *and the acceptor ion with charge* −q. The donor-ion density, in donors per cubic meter, is designated by the symbol N_d, and the acceptor-ion density is N_a. A semiconductor with donor and acceptor atoms is said to be *doped* with impurities; these *dopants* are rigidly fixed in the crystal structure, unable to participate in the conduction process. At a temperature of zero kelvin (−273°C) none of the impurities are ionized, and $N_d = N_a = 0$. Above about 50 K nearly all are ionized, and N_d and N_a become constants independent of temperature. Charged particles other than holes, free electrons, donors, and acceptors are effectively neutralized and can be ignored insofar as our study of device physics is concerned.

A semiconductor not subjected to external disturbing influences, such as an applied electric field or high-energy incident radiation, is said to be in *equilibrium*. The equilibrium hole and free-electron densities are denoted by the symbols p_o and n_o, respectively. When a voltage is applied to the terminals of a semiconductor device, the carrier densities *p* and *n* are, of course, no longer necessarily equal to their equilibrium values.

Postulate 3. *Regardless of the number and types of dopants, the product of the equilibrium carrier densities is*

$$p_0 n_0 = n_i^2 \tag{1-1}$$

with n_i^2 *in silicon representing the expression*

$$n_i^2 = 15 \times 10^{44}\, T^3 e^{-14000/T} \text{ m}^{-6} \tag{1-2}$$

T is the absolute temperature in kelvin units with one unit corresponding to 1°C.

An *intrinsic semiconductor* is one in which p_o and n_o are equal, or at least nearly so. For this case it follows from (1-1) that

$$p_o = n_o = n_i \tag{1-3}$$