DIGITAL INTEGRATED ELECTRONICS

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PREFACE

In 1956 the McGraw-Hill Book company published the text "Pulse and Digital Circuits" coauthored by J. Millman and H. Taub. That book, which undertook to present a rather complete account of the state of the art of digital electronics dealt almost exclusively with vacuum-tube circuits. Semiconductor devices and circuits, which had not long before been introduced, appeared in a single final chapter, added at the last moment, while the book was in production. In the decade that followed semiconductor devices completely supplanted tubes in digital circuitry. In response to this development the same authors prepared a replacement volume "Pulse Digital and Switching Waveforms" which appeared in 1965. In the newer volume the overwhelming importance of the semiconductor was appropriately emphasized and vacuum-tube circuits were presented only incidentally. Now, again after about a decade, the advances in integrated circuitry have prompted this present volume. However, this book is intended as a continuation of the 1965 work rather than as a replacement. Here the present authors have undertaken to describe and analyze all the basic integrated-circuit building blocks from which digital circuits and systems are assembled. As reasonably as is feasible in a textbook, the material presented is up to date. As was the case in the earlier volume, the present authors have taken great pain with the style of pedagogy. We have striven to make the explanations clear and easily understood without sacrificing depth and completeness of presentation. For this reason, we hope that this work will find a place not only in the classroom but also in a program of self-study for a reader who may want to keep informed about current developments.

The material in the text has been used at the City College of New York in a two-semester course offered to junior and senior electrical engineering students and has been used as well as the basis of two graduate courses. This material has also been presented in a two-semester course offered to technical staff members of the Bell Laboratories, to engineering personnel at NASA and at Lockheed, and in short courses offered in the continuing-education program at the George Washington University.

It is assumed that the reader already has a background in semiconductor devices and circuits. Nevertheless we find it useful to provide in Chapter 1 a review of certain special matters pertaining to the operation of semiconductor devices in a *switching* mode. Semiconductors have rather involved and highly nonlinear volt-ampere characteristics. An exact analysis of semiconductor circuits results in considerable mathematical complexity. In Chapter 1 we present some convenient simplifications which lead to quite good and useful approximations.

The first part of Chapter 2 discusses operational amplifiers. Such amplifiers, intended to be operated linearly rather than in a switching mode, are not our proper concern. Still, in a number of cases we find that operational amplifiers appear as components in what are otherwise digital circuits. Furthermore, by a rather natural extension, operational amplifiers lead to the discussion, in the second part of the chapter, of comparators which are indeed important switching devices.

Chapter 3 introduces the concept of logical variables, Boolean algebra, and methods of analyzing circuits composed of logical gates. Karnaugh maps and their various applications are presented. This chapter is complete in the sense that it presumes no prior acquaintance with the subject and explains all the principles of design and analysis of logical circuits required for an understanding of the entire text. On the other hand, the content of this chapter is inevitably included in a course in logic design and, hence, may be bypassed by readers who have already been exposed to this material.

The electronics of logical gates is begun in Chapter 4. The first part of this chapter deals with resistor-transistor logic (RTL) while the second part is concerned with integrated-injection logic (IIL). RTL is not presently used in new design. Yet there are a number of reasons on account of which it is valuable to consider this family of logic. Being the first widely used family of IC logic available, there are in operation many installations in which it is incorporated. Then, again on account of its elegant simplicity, it is an ideal vehicle through which to present many of the basic concepts and principles universally important in the electronics of logical gates. Finally, it bears an interesting topological relationship to IIL which is one of the most recently developed families of logic. Chapter 5 considers diode-transistor logic (DTL). In the family of DTL we find high-threshold logic (HTL), which finds extensive application in highly noisy environments.

Chapters 6 and 7 discuss transistor-transistor logic (TTL) and emitter-coupled logic (ECL) respectively. At the present time these are the most widely used saturating and nonsaturating logic families. Hence the analysis of these families is rather extensive. In ECL particularly, it turns out that some appreciation of the nature of signal transmission over transmission lines is required. Readers who are unfamiliar with transmission line propagation will find an adequate introductory presentation in Appendix A. A more complete discussion appears in Chapter 3 of "Pulse Digital and Switching Waveforms" referred to above. Metal-oxide semiconductor (MOS) logic and complementary-symmetry (CMOS) logic is presented in Chapter 8.

The various families of logic having been considered (Chapters 4 through 8), we begin in Chapter 9 to consider the basic digital structures which are assembled from these gates. Chapter 9 explores in considerable detail the principles of operation of various types of flip-flops and, in addition, analyzes the electronics of the circuitry of a number of representative commercial units. We take considerable pains to make clear how flip-flops are adapted to circumvent timing problems that would otherwise develop in synchronous systems. Registers and counters are discussed in Chapter 10. Procedures for the design of both synchronous and ripple counters of arbitrary modulo are explained, and the use of registers to generate pseudorandom and other specified sequences is also presented.

Logic circuits for performing arithmetic operations are considered in Chapter 11. Emphasis is placed on the operations of addition (and subtraction) since generally multiplication and division are performed by algorithms involving the operation of addition (or subtraction). We have taken rather more care than is usual to explain clearly how negative numbers are expressed and how subtraction is effected in one's-complement and two's-complement notation through the use of logic circuitry which actually performs addition. The use of saturation logic for overflow correction in addition is presented as is the operation of the *arithmetic logic unit* which is the heart of every *microprocessor*. Semiconductor memories are examined in Chapter 12. We have omitted core memories since it appears that such core memories are in the process of being supplanted by semiconductor systems. This chapter includes sequential memories, read-only memories and random-access dynamic and static memories. The electronics of memories involving field-effect transistors, the CCD and bipolar junction transistors are also described.

In Chapters 13 and 14 we consider the matter of the interface between digital and analog signals. Chapter 13 presents analog gates, analog multiplexers, sample-and-hold circuits, integrate-and-dump circuits, etc. Chapter 14 examines digital-to-analog and analog-to-digital systems. The various analog-to-digital systems considered are reasonably representative of the systems which are in wide use. Finally, in Chapter 15, timing circuits—the integrated-circuit equivalents of monostable and astable multivibrators—are discussed.

The circuits presented in this text are typical of those encountered in the field. More than 400 homework problems are provided, ranging from routine exercises to rather sophisticated design problems. A solutions manual is available which instructors can obtain from the publisher. An answer book is also available. The authors will be happy to furnish a set of laboratory experiments currently used at CCNY in conjunction with this text.

We acknowledge gratefully the encouragement given by our colleagues and students. In particular we thank Mr. T. Apelewicz who prepared the solutions manual, Dr. J. Garodnick to whom we are indebted for a critical review and criticism of much of the text material and Mr. Edward Tynan and Dr. Ronald Schilling through whose kindness we were able to receive a great deal of the very useful technical literature published by the Motorola company. We express our particular appreciation to Mrs. Joy Rubin for her skillful service in typing the manuscript.

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CONTENTS

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ELECTRONIC DEVICES

As with analog circuits, the electronic devices used in digital processing circuits include the diode, the bipolar transistor, and the field-effect transistor. We assume that the reader is familiar with these devices but principally in applications involving analog circuitry, where they are used as linear elements. In digital circuits, these devices are used principally in a nonlinear manner, i.e., in a switching mode, where they are abruptly driven between the extremes of nonconduction and conduction. In this chapter we shall review some matters of interest in connection with these devices with special emphasis on their behavior when used as switches.

1.1 THE IDEAL SEMICONDUCTOR DIODE

For an ideal *pn* junction diode the current I is related to the voltage V by the equation

$$I = I_0(\epsilon^{V/V_T} - 1) \qquad (1.1\text{-}1)$$

As indicated in Fig. 1.1-1*a*, the current I is positive when the current flows

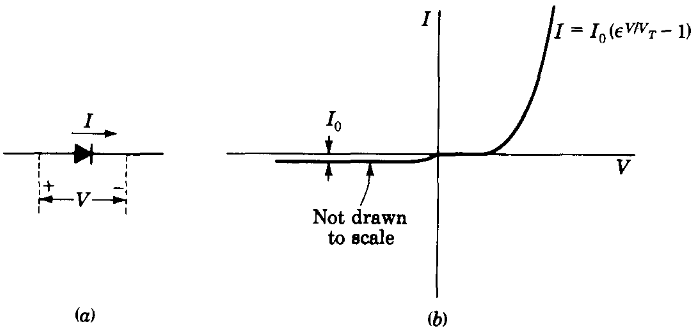

FIGURE 1.1-1
(*a*) The symbols *I* and *V* used in the diode equation (1.1-1), defined. (*b*) The volt-ampere characteristic of an ideal diode.

from the *p* side to the *n* side of the diode. The voltage *V* is the voltage drop from the *p* side to the *n* side. When *V* is positive, the diode is forward-biased. The symbol V_T stands for the electronvolt equivalent of the temperature and is given by

$$V_T \equiv \frac{kT}{e} \tag{1.1-2}$$

where k = Boltzmann constant = 1.38×10^{-23} J/K
e = electronic charge = 1.602×10^{-19} C
T = absolute temperature, kelvins

Substituting, we find that $V_T = T/11{,}600$ V and that at room temperature ($T \approx 300$ K) $V_T \approx 25$ mV.

The form, in principle, of the diode volt-ampere characteristic is shown in Fig. 1.1-1*b*. When the voltage V is positive and several times V_T, the exponential term in Eq. (1.1-1) greatly exceeds unity and the -1 term in the parentheses may be neglected. Consequently, except for a small range in the neighborhood of the origin, the current increases exponentially with voltage. When the diode is reversed-biased and $|V|$ is several times larger than V_T, $|I| \approx I_0$. The reverse current is therefore constant, independently of the applied reverse bias. Accordingly, I_0 is referred to as the *reverse saturation current.* This current is shown in Fig. 1.1-1*b* using a greatly enlarged scale since the value of I_0 is orders of magnitude less than typical values of I.

As noted, we shall be interested in the operation of diodes (and other elements) as switches. The diode is an *open* switch when back-biased and a *closed* switch when forward-biased. We shall generally find, in circuits of interest to us, that when a diode is called upon to make its presence felt in a circuit as a closed switch, it may typically carry a current of the order of a milliampere, i.e., in the range 0.1 to 10 mA. How large a voltage must be impressed across the diode to produce this nominal forward current depends, of course, on the diode cross section. If a diode yielded a forward current of 1 μA at an applied voltage V, a second diode of cross section 1,000 times larger would yield a current of 1 mA.

When a diode is manufactured, whether as a discrete component or an element in an integrated circuit, it is economical to use a cross section no larger than necessary. Such is particularly the case in integrated circuits (IC). For here, since many circuit elements are included on a single chip, a small increase in the cross section of one element is multiplied many-fold. This may result in an appreciable increase in the size of the silicon chip, or, equivalently, the same size chip will contain fewer diodes. The cross section of a diode will then be selected in part on the basis that with a reasonable margin of safety the diode should be able to dissipate the heat generated within it without an unacceptable increase in temperature. Additionally, the cross-sectional area must be large enough to reduce the ohmic resistance of the diode to an acceptable value.

A diode model When we examine the volt-ampere characteristics of commercial silicon diodes intended for application in low-power electronic circuits, we find that currents of the order of a milliampere correspond to a forward voltage of about 0.75 V. Diodes incorporated into integrated circuits appear to have comparable characteristics, again requiring about 0.75 V for forward currents in the range of a milliampere. Since we shall frequently have occasion to refer to this voltage, we assign to it a symbol $V_\sigma = 0.75$ V. When, then, the forward diode voltage is V_σ, the diode, used as a switch, is in the closed position.

If the diode switch is to be in the open position, it is really not necessary, as a matter of practicality, that the diode be reverse-biased. It is only necessary that the voltage across the diode correspond to a forward current which is negligibly small in comparison with the current corresponding to V_σ. Let us consider that the diode current is negligible when it has been reduced to 1 percent of the current corresponding to V_σ. The diode voltage, corresponding to this reduced current, we call V_γ.

If currents I_σ and I_γ correspond to voltages V_σ and V_γ, then from Eq. (1.1-1), we have

$$I_\sigma = I_0(\epsilon^{V_\sigma/V_T} - 1) \tag{1.1-3a}$$

and

$$I_\gamma = I_0(\epsilon^{V_\gamma/V_T} - 1) \tag{1.1-3b}$$

Since ϵ^{V_σ/V_T} and ϵ^{V_γ/V_T} are each much greater than unity, we have

$$\frac{I_\sigma}{I_\gamma} = 100 = \epsilon^{(V_\sigma - V_\gamma)/V_T} \tag{1.1-4}$$

Hence

$$V_\sigma - V_\gamma = V_T \ln 100 \approx 120 \text{ mV} \tag{1.1-5}$$

Thus, since $V_\sigma \approx 0.75$ V, $V_\gamma \approx 0.63$ V.