DISCRETE
AND INTEGRATED
ELECTRONICS

ERVINE M. RIPS

DISCRETE AND INTEGRATED ELECTRONICS

ERVINE M. RIPS
New Jersey Institute of Technology

Prentice-Hall, Englewood Cliffs, New Jersey 07632

Library of Congress Cataloging-in-Publication Data

Rips, Ervine M. (date)
Discrete and integrated electronics.

Includes index.
1. Analog electronic systems. 2. Integrated circuits. 3. Digital electronics. I. Title.
TK7870.R53 1986 621.381 85-16971
ISBN 0-13-215153-7

Editorial/production supervision and interior design: **Diana Drew**
Cover design: **Whitman Studio, Inc.**
Manufacturing buyer: **Rhett Conklin**

A Division of Simon & Schuster, Inc.
Englewood Cliffs, New Jersey 07632

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

ISBN 0-13-215153-7 025

Prentice-Hall International, Inc., *London*
Prentice-Hall of Australia Pty. Limited, *Sydney*
Editora Prentice-Hall do Brasil, Ltda., *Rio de Janeiro*
Prentice-Hall Canada Inc., *Toronto*
Prentice-Hall Hispanoamericana, S. A., *Mexico*
Prentice-Hall of India Private Limited, *New Delhi*
Prentice-Hall of Japan, Inc., *Tokyo*
Prentice-Hall of Southeast Asia Pte. Ltd., *Singapore*
Whitehall Books Limited, *Wellington, New Zealand*

Preface

Electronic systems today are based more upon integrated circuits than on discrete elements. Nevertheless, discrete transistors and diodes are still widely used, especially in high-power applications. Moreover, to make effective use of the ubiquitous IC building blocks, it is necessary to have some idea of how their internal, discrete elements work. We have, therefore, two reasons to study the electronics of discrete elements—first, to allow us to use discrete elements as such, and second, to understand how they function in integrated circuits.

Necessary as such a micro approach may be, it is not sufficient. We must also work on a macro level to understand the operation of larger scale systems whose elements are integrated circuits. In this book I have tried to give adequate treatment to both points of view.

Emphasis is placed on analog circuits. However, since we seem to be living in a world that is becoming increasingly digital, I have devoted three chapters to topics from that area. Chapter 2 deals with the internal structure and operation of basic logic gates. Chatper 11 treats memory devices—from basic flip-flops to RAMs and ROMs. Chapter 12 is devoted largely to those devices that operate at the analog-digital interface—analog comparators, D/A and A/D converters. In the discussion of digital devices I have chosen not to introduce such topics as Boolean algebra or Karnaugh maps; these matters are better left to books that concentrate on digital circuits.

You will find certain departures from what is usually found in a book of this sort. The first of these is the treatment of feedback, which stresses the asymptotic gain formula and Blackman's impedance formula. This approach obviates the troublesome and often confusing classification of input and output circuits as shunt- or series-connected. For those who want to connect the two approaches, conventional feedback-circuit classification is reviewed in Appendix A.

Other departures from standard textbook treatments are the discussion of the differential amplifier and its related current-source circuitry and the detailed discussion of direct-coupled structures such as those used in the internal configuration of operational amplifiers. The applications of operational amplifiers that are considered include inductance and capacitance simulation, band-pass and notch filters, and power supply regulators.

Listings of eleven computer programs are given at appropriate points in the text. These allow computation of such things as the gain-bandwidth product for a common-emitter amplifier, gain and phase crossover points when DC gain and the real poles of an amplifier are given, and pole locations for low-pass and band-pass Butterworth amplifiers. The programs are written in BASIC and are suitable for use on a personal computer.

The book is intended for use by fourth-year students in electrical engineering technology. It may also be useful for third-year electrical engineering students. The chief distinction between students in these two programs is the higher level of mathematical proficiency expected of those in engineering. However, in either curriculum the study of electronic circuits requires very little mathematical sophistication. For those students who are interested, I have tried to provide adequate mathematical explanations and derivations where these are appropriate and to do so in a direct manner. The instructor may, of course, elect to omit some of the more abstract derivations and proceed directly to the application of the principles involved.

For technology students, there is more material here than can be covered in one semester. If the students come to the course well prepared, the instructor might select Chaps. 3, 4, 5, 6, 7, 11, and 12. Another possible selection is Chaps. 1, 3, 4, 7, 9, and 10.

Every section includes worked-out, numerical examples. Problems at the ends of chapters rarely require derivations but can usually be solved using only simple arithmetic in a two- or three-step logical process. Plug-in problems have been avoided and the few that are included serve only to illustrate the magnitude of the quantities involved. An Instructor's Manual is available.

I am pleased to acknowledge the helpful suggestions of my colleagues, particularly Solomon Rosenstark, who brought to my attention the utility of the asymptotic gain formula and Blackman's equation. Discussions with Joseph Frank helped to clarify a number of ideas.

Thanks are also due to Nancy Bogen who provided encouragement and support during early phases of the writing.

—Ervine M. Rips

Contents

CHAPTER 1

Review of Basic Principles of Semiconductor Devices

1-1 JUNCTION TRANSISTOR OPERATION

A fundamental element of many semiconductor devices is the *pn* junction. Such junctions are usually formed by diffusing an *n*-type doping material through some depth of a *p*-type base material.

We can gain some understanding of the action of *pn* junctions by recalling that the *p* region contains a certain population of mobile holes, whereas the *n* region contains mobile electrons. At the junction, some holes diffuse into the *n* material and some electrons diffuse into the *p* region. Bear in mind that the holes were produced by *p*-doping elements, whose nuclei have one *less* positive charge than the surrounding silicon (or germanium) nuclei. Likewise, the electrons originated from *n*-doping elements, whose nuclei have one *more* positive charge than the neighboring silicon nuclei. When the mobile electrons and holes diffuse across the junction, they leave behind these nuclei, which—of course—are locked, immovable, in the crystal structure. Thus the region on the *p* side is deficient in positive charge, but the region on the *n* side has excess positive charge. The resulting situation is illustrated in Fig. 1-1.

A depletion region is thus formed in the immediate vicinity of the junction, which results in a built-in potential. If we connect an external battery-resistor circuit to the *pn* terminals, we have the situation shown in Fig. 1-2.

Looking at the circuit analogs, we see that in (a) and (b), the external battery and the built-in potential are *aiding*, while in (c) and (d), they are *in opposition*. From this we conclude that if the external source is polarized to direct current *into*

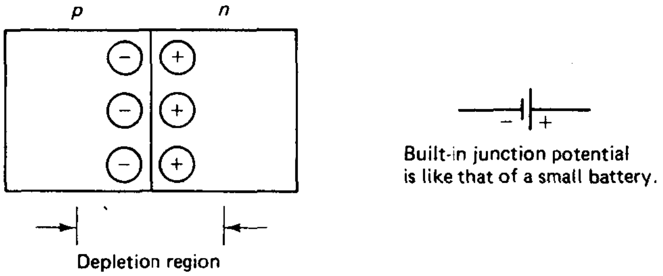


Fig. 1-1 *pn* junction showing excess positive and negative charges resulting from stripped nuclei.

the *p side* of the junction, current can be made to flow *easily*. But if we attempt to direct current *into* the *n side*, current flows only with difficulty.

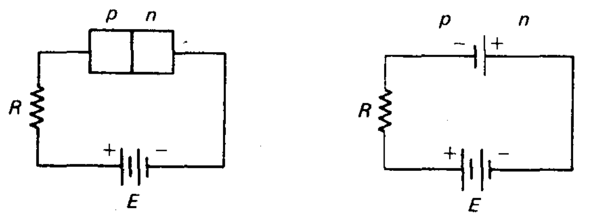
Thus a *pn* junction has *rectifying* properties. The current direction from p to n is called the *forward* direction. The direction from n to p is called the *reverse* direction. The relation between p and n regions and the conventional circuit symbol for a diode is illustrated in Fig. 1-3.

If we connect a semiconductor diode as shown in Fig. 1-4(a) and vary the voltage V applied across it, the current I will behave as shown in the curve of Fig. 1-4(b).

The equation that relates I to V is

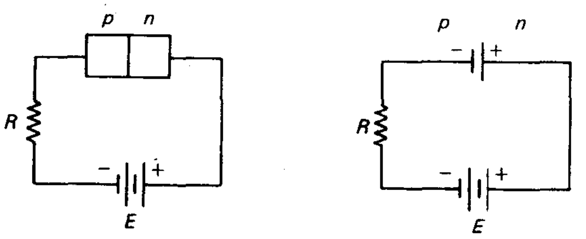
$$I = I_s(e^{qV/kT} - 1) \tag{1-1}$$

where q and k are constants, T is the junction temperature in degrees Kelvin, and I_s is a quantity called the *reverse saturation current*. For V positive (forward) and equal to only a few tenths of a vote, I will be positive and will increase rapidly. But when V is negative (reverse), the term $e^{qV/kT}$ becomes negligible, so that I is approximately $-I_s$.



(a) Actual circuit

(b) Analog of circuit (a)

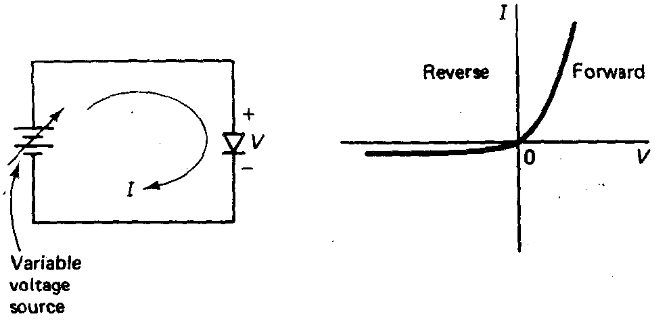


(c) External battery reversed

(d) Analog of circuit (c)

Fig. 1-2 An external battery-resistor circuit connected to the *pn* junction.

Fig. 1-3 Diode symbols.

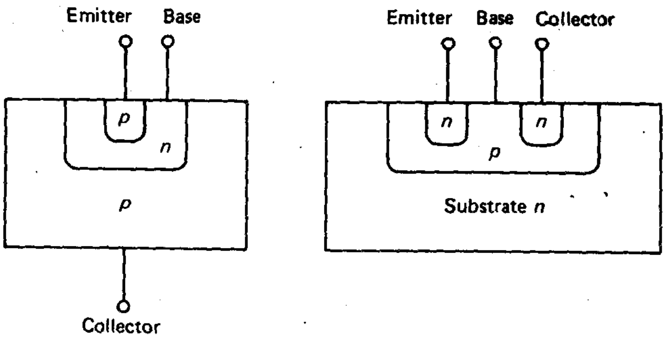


(a) (b)

Fig. 1-4 Diode volt-ampere characteristics.

Junction transistors are formed by successive diffusions of *n* and *p* doping materials to yield structures like those shown in Fig. 1-5. Since both types of material are used to form these transistors, they are often called bipolar junction transistors or BJTs.

To understand transistor action, we use the schematic structure shown in Fig. 1-6. The batteries shown in Fig. 1-6 are meant to suggest bias polarities for the two internal junctions. We can see that the left-hand *np* junction is *forward* biased, whereas the *pn* junction on the right is *reverse* biased. Thus current flows readily through the left-hand junction, in the direction shown. This indicates that electrons are injected from the left-hand *n* body through the junction into the *p* region. These electrons diffuse through the *p* material until they encounter the strong electric field that exists at the reverse-biased junction on the right. At that point they are pulled through the junction, exiting to the right. Thus a current must enter the right-hand *n* body as shown.



(a) A *pnp* transistor (b) An *npn* transistor

Fig. 1-5 Transistor structures.

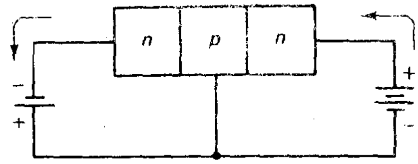


Fig. 1-6 Schematic transistor structure showing normal directions of operating current.

Not all the electrons injected at the left junction arrive at the one on the right because a certain number of them recombine with the holes that are present in the *p* region. (Remember, a hole is the absence of an electron.) For this reason only a fraction of electrons *emitted* at the left are *collected* at the right. (You will recall that the transistor structure consists of an emitter, a base, and a collector.) Thus we see that the collector current is related to the emitter current by the equation

$$I_C = \alpha I_E \tag{1-2}$$

By Kirchhoff's current law, we can see that the current into the base must be given by

$$I_B = I_E - I_C = (1 - \alpha)I_E \tag{1-3}$$

Typical values of α are 0.98 and 0.99. This number varies from one device to another.

1-2 JUNCTION TRANSISTOR BIASING

Before considering circuits that amplify or control signals, we first have to establish DC operating conditions. Perhaps the best way to review the procedure for doing so is by means of an example.

Example 1.1

A typical *npn* transistor circuit is shown in Fig. 1-7. (Note that the arrow on the emitter symbol points in the direction of normal-operating, emitter-current flow.) The problem here is to determine R_B so that I_E will be 1 mA. To solve this problem we need to know how much voltage will appear across the base-emitter junction. One way to find out would be to include in our equations a solution for V_{BE} taken from Eq. (1-1). But to do so would be needlessly complicated and not very useful. Instead, we simply make use of a fact, based on many observations, that in normal, forward bias, the voltage V_{BE} for a silicon transistor is usually about 0.7 V.

For $I_E = 1$ mA,

$$I_B = (1 - \alpha) \times 1 \text{ mA}$$

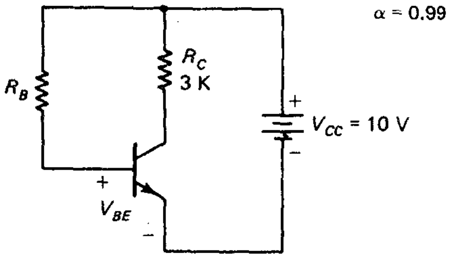


Fig. 1-7 Transistor circuit.

or

$$I_B = (1 - 0.99) \cdot 10^{-3} = 10\ \mu\text{A}$$

To find R_B we observe that

$$V_{CC} = V_{RB} + V_{BE}$$

Hence V_{RB}, the voltage across R_B, must be

$$V_{RB} = 10 - 0.7 = 9.3\ \text{V}$$

Then $R_B = V_{RB}/I_B$, or $R_B = 9.3/10^{-5} = 9.3 \times 10^5 = 930\ \text{K}\Omega$.

Sometimes, when V_{CC} is large compared to V_{BE}, we can neglect V_{BE} altogether with little effect on the results.

It is interesting to observe that, in Example 1-1, the voltage from collector to emitter is $V_{CE} = V_{CC} - I_C R_C$. Since $I_C \approx I_E$ we can calculate V_{CE} quite simply.

$$V_{CE} = 10 - 10^{-3} \times 3 \times 10^3 = 10 - 3 = 7\ \text{V}$$

It is convenient to define a parameter that relates base current to collector current directly in dealing with circuits like the one in Fig. 1-7. Since $I_B = (1 - \alpha)I_E$ and $I_C = \alpha I_E$, then

$$I_B = \left(\frac{1 - \alpha}{\alpha}\right) I_C \quad \text{or} \quad I_C = \frac{\alpha}{1 - \alpha} I_B$$

We can define the quantity h_{FE}, sometimes taken as β, to be

$$h_{FE} = \beta = \frac{\alpha}{1 - \alpha} \tag{1-4}$$

Then we can write

$$I_C = h_{FE} I_B \tag{1-5}$$

A word of caution: Eq. (1-5) takes no account of the presence of a reverse-bias current I_{CBO} through the collector-base junction. When the transistor is connected as shown in Fig. 1-7, this current is magnified by a factor $1 + h_{FE}$. The correct equation should therefore be

$$I_C = h_{FE} I_B + (1 + h_{FE}) I_{CBO}$$

To make matters even more complicated, I_{CBO} is temperature sensitive. However, its value for silicon transistors is usually extremely small. Consequently, since our purpose here is only to review a few basic principles, we shall ignore it. You are advised to review material from previous courses that deal with this matter.

A commonly used biasing circuit is shown in Fig. 1-8. We analyze it in Example 1.2.

Example 1.2

The problem is to find the collector current and the collector-emitter voltage. We begin by assuming that the base current will be small compared to the current through R_2 and R_1', which are connected in series across V_{CC}. We shall check this

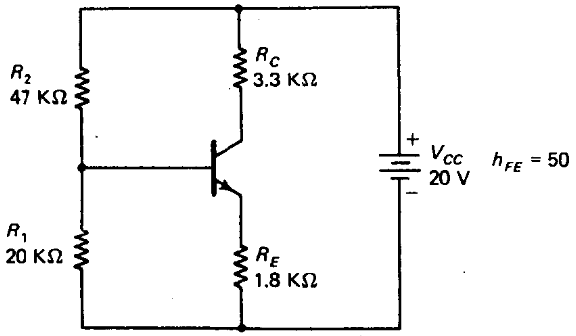


Fig. 1-8 Circuit example.

assumption later. The voltage at the base terminal is, by the voltage-divider rule, 20 × (20 KΩ)/(20 KΩ + 47 KΩ) = 20 × 20/67 ≈ 6 V. Since the base-emitter voltage V_{BE} is 0.7 V, the emitter voltage is 6 − 0.7 = 5.3 V. This must be the voltage *across* R_E, so that $I_E = 5.3/1.8\text{ K} = 2.94\text{ mA} \approx 3\text{ mA}$. The voltage *drop across* R_c must therefore be very nearly 3 mA × 3.3 K = 9.9 V. To find the collector-emitter voltage, we use Kirchhoff's voltage law and write

$$V_{CC} = V_{RC} + V_{CE} + V_{RE}$$

or

$$20 = 9.9 + V_{CE} + 5.3.$$

$$V_{CE} = 20 - 9.9 - 5.3 = 4.8\text{ V}$$

What about our assumption that I_B is small compared to the current through R_2 and R_1? First of all,

$$I_B = \frac{I_E}{1 + h_{FE}} = \frac{3 \times 10^{-3}}{51} \approx 0.06 \times 10^{-3}$$

$$= 60\ \mu\text{A}$$

The current through R_1 and R_2 is 20/(20KΩ + 47 KΩ) = 20/67 mA, or about 0.3 mA = 300 μA. Thus the assumption appears to be of doubtful validity since the base current is 20% of the current through the voltage divider. Ordinarily, we consider that our assumption is reasonable when I_B is no more than 10% of the voltage-divider current.

What can be done about this situation? To answer this question, we begin by calculating the resistance that is seen looking into the base terminal. The current into the base is, of course, I_B. The voltage *due to* R_E is

$$I_E R_E = (1 + h_{FE}) I_B R_E$$

Then the DC resistance looking into the base must be given by

$$R_{\text{base-to-ground}} = R_{B_{in}} = \frac{\text{base-to-ground voltage}}{\text{current into base}} = \frac{(1 + h_{FE}) I_B R_E}{I_B}$$

or

$$R_{B_{in}} = (1 + h_{FE}) R_E$$