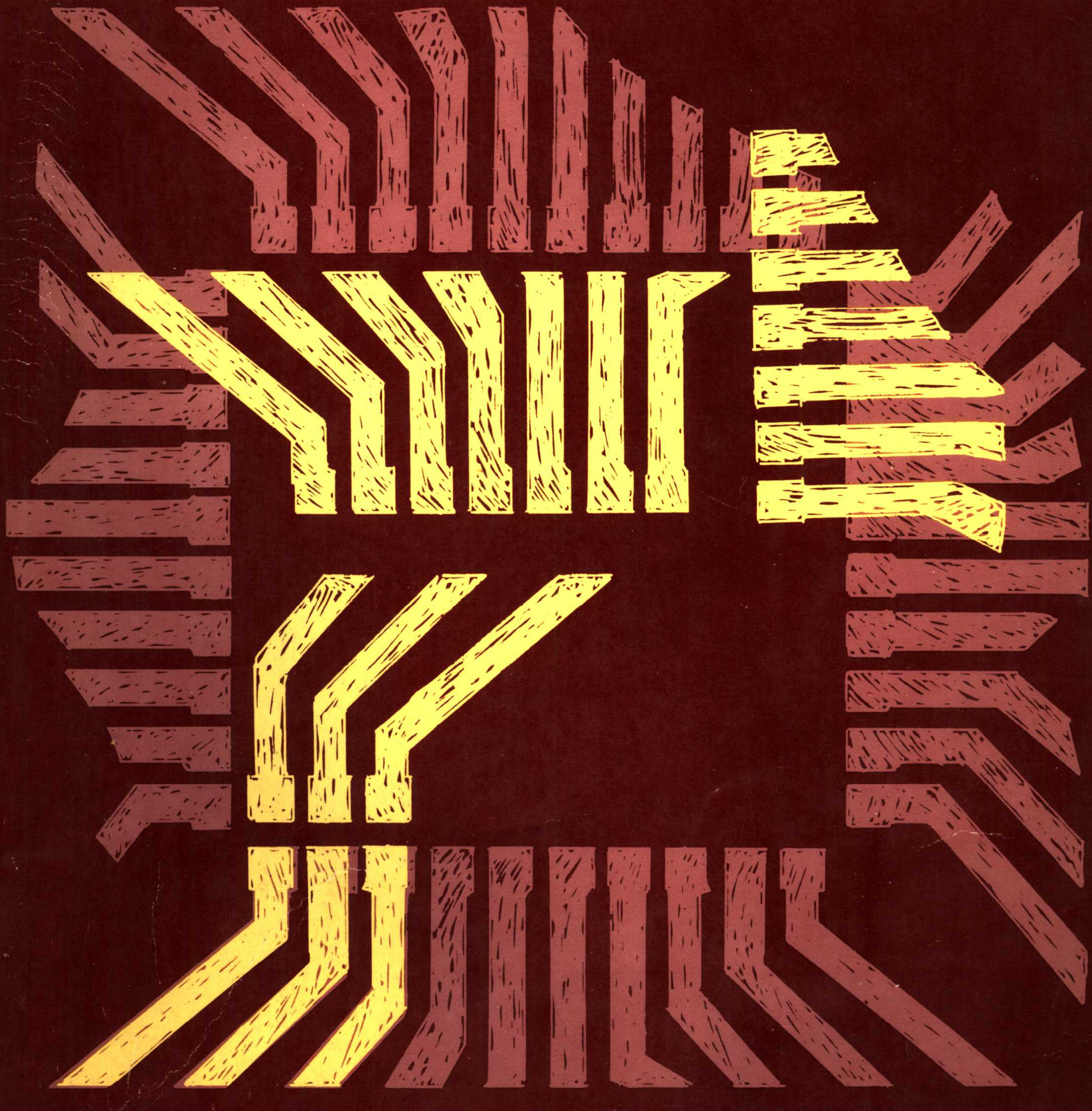
Integrated Circuits For Electronics Technicians

Edward Pasahow



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For my mother and father.

Library of Congress Cataloging in Publication Data

Pasahow, Edward.
Integrated circuits for electronics technicians.

Includes index.
1. Integrated circuits. I. Title.
TK7874.P38 621.381'73 78-8742
ISBN 0-07-048710-3

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1234567890 WCWC 7854321098

The editors for this book were George J. Horesta and Mark Haas, the designer was Eileen Thaxton, the art supervisor was George T. Resch, and the production supervisor was Regina R. Malone. It was set in Caledonia by Progressive Typographers.
Printed and bound by Webcrafters, Inc.

PREFACE

This book has one main purpose, that of presenting a state-of-the-art study of integrated circuits. It was written because no existing text offered a modern approach to these devices at the level of a student working for the Associate of Arts degree. Hobbyists and engineers who want to increase their understanding of practical integrated circuit theory and applications will also find this text useful. The unique integration of theory with experiments provides not only a description of idealized devices, but also an appreciation of actual circuit operation.

Current practice in the field has guided the presentation throughout. The use of state tables to complement timing diagrams in the study of sequential circuits furnishes the student with a powerful analytical tool. The coverage of I^2L, Schottky TTL, SOS, bubble memories, charge-coupled devices, and microprocessors along with more traditional topics (TTL, MOS, combinatorial and sequential circuits, memories, and linear circuits) assures a complete overview of today's electronic systems.

The mathematics is limited to basic college algebra, and no previous student exposure to integrated circuits is assumed. New techniques such as Boolean algebra and number systems are fully developed in the chapters in which these subjects appear. The text material can be used in lecture and laboratory courses with several different approaches. A basic digital circuits course, a computer circuits course, or a course emphasizing integrated circuits other than those used in computers can be developed from this book. The latter is covered in my classes at San Diego Community Colleges.

A suggested one-semester sequence for the basic digital circuits course would draw from Chapters 1 through 10, omitting the optional material marked with a vertical line down the left-hand margin.

The advanced computer circuits course should be preceded by a number systems and Boolean algebra prerequisite. Coverage would include:

Chapter **1**	Chapter **6**
Chapter **2** (review only)	Chapter **7**
Chapter **3**	Chapter **8**
Chapter **4**	Chapter **9**
Chapter **5** (review only)	Chapter **12**

The course emphasizing other integrated circuit applications would follow the sequence:

Chapter **1**	Chapter **6**
Chapter **2** (omit optional material)	Chapter **7**
Chapter **3**	Chapter **9** (omit optional material)
Chapter **4**	Chapter **10**
Chapter **5** (omit optional material)	Chapter **11**

Proper acknowledgement for the help which so many others provided me with in writing this book can hardly be expressed. The comments and suggestions by students in my courses have been of great assistance in clarifying the presentation and correcting errors. Their review has greatly strengthened the text. But without the particular encouragement and assistance along the way from Rosemarie Pasahow this book would never have been written.

Edward Pasahow

CONTENTS

CHAPTER ONE
INTRODUCTION TO INTEGRATED CIRCUITS

Numbers are all around us. Every day numerical displays confront us at work, in our homes, and even during our leisure time. Annual sales of 60 million calculators, 30 million electronic watches, and 10 million digital games prove the popularity of integrated circuit technology. Digital equipment has advanced from its original position as a minor area of specialization to a point where it occupies an estimated 80 percent of the electronics market. This emphasis on digital electronics means that anybody developing, testing, or maintaining electronic equipment must understand digital logic and control systems.

Integrated circuits are a major cause of this change from analog to digital methodology. These small packages provide simple, low-cost solutions to designing and manufacturing electronic devices. Inexpensive pocket calculators, digital clocks, and microprocessors are some results of the shift away from discrete components. In fact, these products could not exist without the integrated circuit.

Even in analog applications integrated circuits have grown in importance. The same economic factors that make integrated circuits practical for digital components also affect analog equipment manufacture. As this trend continues to grow, electronic technology will become even more committed to replacing discrete transistors, resistors, and capacitors with integrated circuitry.

CHAPTER OBJECTIVES

Upon completing this chapter you should be able to:

1. Discuss the advantages of integrated circuits.
2. List the processes used to manufacture integrated circuits.
3. Describe the electronic components that comprise integrated circuits.
4. Discuss crystal growth, epitaxial growth, solid-state diffusion, and ion implantation processes which introduce controlled impurities during the manufacture of semiconductors.
5. List the steps in constructing a monolithic integrated circuit.
6. Distinguish between various types of pulse signals.

HOW TO USE THIS BOOK

Before we start, a brief explanation of how this book is put together should help make your study time more effective. Each chapter begins with a list of objectives. These objectives concisely describe what you should have learned by the time you have completed the chapter. A review at the end of each section lets you check your understanding of the material just covered before you go on to a new section.

The chapter summaries show you how each topic fits together as a whole and how the topics satisfy the chapter objectives. Included as part of the summary is a list of key terms and concepts that help you see how well you have grasped the most important points of the subject. The problems allow you to test your knowledge of the subject and identify areas where you may need further study. Finally, the experiments relate the theoretical discussion to actual circuit applications. This opportunity to see how real integrated circuits differ from the idealized models is an especially important facet of learning about them.

INTEGRATED CIRCUITS

Integrated circuits are composed of transistors, diodes, resistors, and capacitors used in combination. These circuit elements are inseparable from the base material, called the *substrate*. Each circuit is produced as a microscopic network on the substrate.

A major advantage of integrated circuitry is the resulting reduction in the number of discrete electronic components. As Fig. 1-1 shows, the number of components in a single integrated circuit has risen from less than 10 to more than 100,000 in 20 years. As the circuits grew more complex, the costs began falling, as Fig. 1-2 shows, making the use of integrated circuits economically attractive. Simplified designs and modular circuits with fewer interconnections also cut costs. To these factors add small size, low power requirements, increased speed, and improved reliability—and the reasons why integrated circuits are increasingly being selected become obvious.

Even in the beginning, demand for these circuits was high. Miniature electronic systems built with resistor arrays were used during World War II. The wiring and resistors in the arrays were manufactured by screen-printing silver paste and resistive ink on a ceramic substrate. When the transistor was invented in 1947, a major obstacle to developing the integrated circuit was overcome. The first monolithic integrated circuit with a single transistor, two

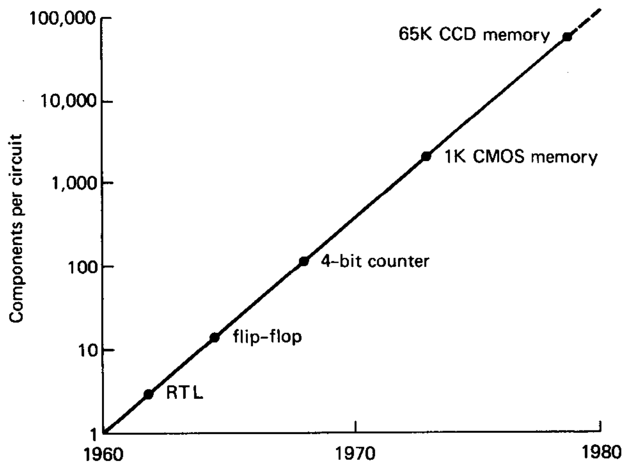


Figure 1-1. Number of components in integrated circuits.

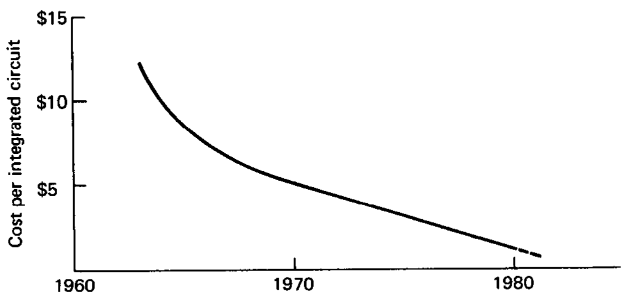
resistors, and a resistor-capacitor network was demonstrated in 1958.

As the need for integrated circuits grew, several manufacturing processes for them evolved. The *monolithic* method of circuit manufacture builds the elements within or on top of the semiconductor substrate. The *multichip* circuit process requires microassembly of two or more chips on a single substrate. The substrate supplies the interconnections and isolation for the chips. *Vacuum-deposited films* are used in a third type of integrated circuit; these can be further divided into *thin* and *thick films*. The elements are formed of films deposited on the substrate. Usually only passive components such as resistors and capacitors can be fabricated by the film process. Combining monolithic and thin-film elements produces *hybrid circuits*. Each of these fabrication processes and their effects on the structure and properties of the integrated circuit will be discussed further in the following paragraphs.

Monolithic Circuits

Monolithic circuits are formed layer by layer in a three-dimensional network of conductors, insulators, and semiconductors. A variety of circuits can be produced during the processing sequence by changing the pattern, or *mask*, for each of the

Figure 1-2. Cost of integrated circuits.



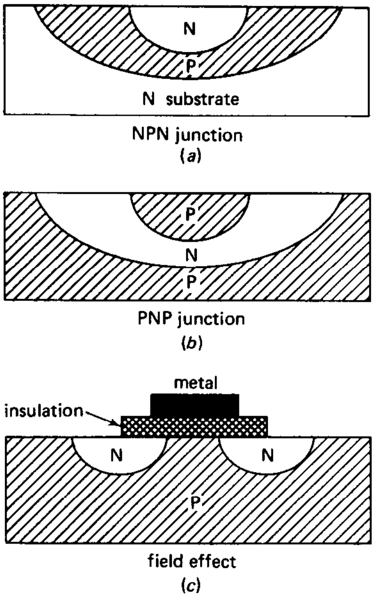


Figure 1-3. Transistors.

layers. The mask covers an area larger than a single circuit and repeats the same pattern across an entire semiconductor wafer. (The semiconductor is usually silicon.) So from 100 to 1000 complete circuits are produced at one time.

Structurally the electronic components of the circuit include diodes, transistors, and passive elements. Just as in discrete semiconductors, the P-type material has an excess of positive majority carriers ("holes") resulting from a precise "doping" level of impurities added to the silicon. The N-type material has an excess of negative majority carriers (electrons) also produced by the dopant. The boundary between two regions of P- and N-type materials forms the junction of a diode.

Transistors can be produced in either bipolar or field-effect form as shown in Fig. 1-3. The bipolar or junction transistor has two adjacent PN junctions; the field-effect device has separate PN junctions spaced along the surface.

Resistors can be formed from the semiconductor, which is itself a relatively poor conductor. Regions of either P- or N-type material with uniform conductivity are used. Capacitors require that a dielectric and a metal electrode layer be placed over the semiconductor, which acts as the second electrode. The insulator and the two electrodes form the capacitor.

Film Circuits

Elements are deposited on either glass or ceramic to produce thin-film components. Resistors are created from nickel-chromium alloys, tantalum, tantalum nitride, or metal silicides mixed with other metals and insulators (cermets). The precise amount of resistance is adjusted by vaporizing the film with a laser while monitoring the resultant resistor value. Capacitors are simply a layer of dielectric between two conductors. Thick-film circuits use special inks printed through silk-screen masks. After they have been fired in an oven, the inks become resistors, conductors, or insulators. Resistor values are adjusted by grinding away the material.

Hybrid Circuits

Making hybrid circuits by attaching and connecting the terminals of the semiconductor chips to films requires one of three procedures: (1) The chip may merely be soldered to a metallized pad on the substrate and fine wires are welded between the chip electrodes and the film. (2) The *inverted assembly* process uses solder-coated metal balls to join the chip to the substrate. (3) Metal fingers protruding from the chip are welded to the film in the *beam lead* method.

Monolithic Circuit Fabrication

A simplified example of the steps necessary to make a monolithic circuit will indicate the complexity of the modern fabrication techniques which produce such circuits as the one shown in Fig. 1-4. The process almost always starts with a single crystal of silicon that was pulled from a melt. The crystal is sliced into disks 2 inches [50 millimeters] or more in diameter and about 0.01 inch

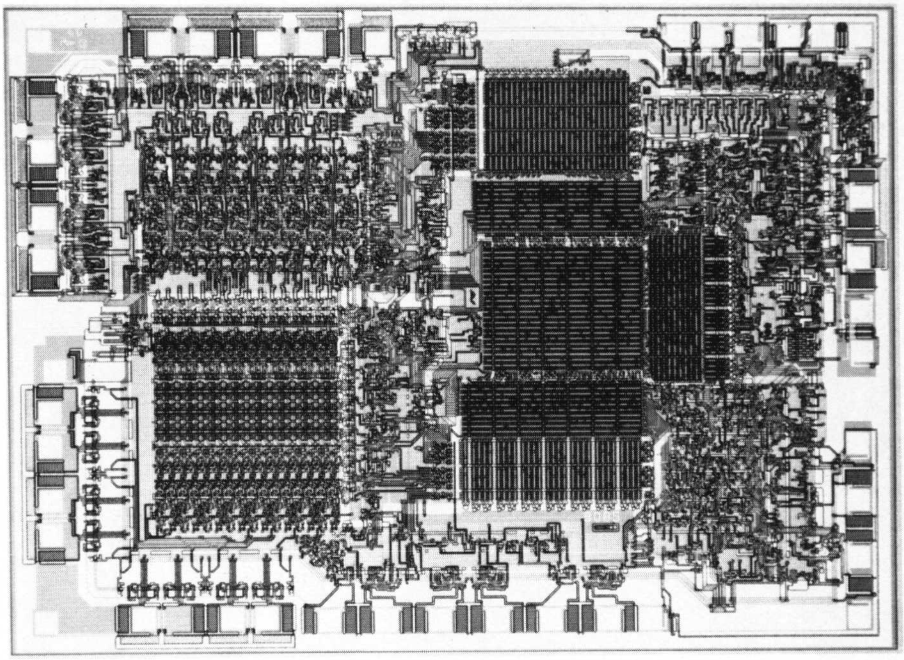


Figure 1-4. Microprocessor integrated circuit (Intel Corporation).

[0.25 millimeter] thick. After they have been lapped and polished, these wafers have a mirrorlike surface.

Impurities have to be introduced to change the silicon to either P- or N-type. Impurities can be introduced during crystal growth by adding the dopant to the melt. Alternatively, doping can be accomplished by *epitaxial growth.* That is, the wafer is heated to 1000 to 1300°C in an atmosphere consisting of a doped silicon compound. Silicon from the compound deposits on the wafer as a continuation of the single crystal lattice. *Solid-state diffusion* is yet another method of depositing impurities on the surface when it is heated to 1000 to 1300°C. The impurity atoms enter the crystal lattice and diffuse into the silicon as a shallow layer. A photoengraved mask limits the areas where impurities can enter. Finally, the *ion implantation* method accelerates impurity ions with a voltage potential (50 to 500 kilovolts) and causes them to strike the silicon. The kinetic energy of the ions causes them to penetrate the crystal. This low-temperature process makes sharp gradients between P- and N-type materials possible and provides precise doping levels.

Figure 1-5 shows the series of steps involved in processing a wafer to prepare a simple monolithic integrated circuit (IC). After the silicon substrate—here P-type material—has been prepared for processing, the surface is oxidized. Silicon dioxide is glass, which is an excellent insulator. The oxide layer is etched in some areas to form a mask with windows to limit the growth of the next layer (Fig. 1-5*c*). Then N-type impurities are diffused into the substrate to form the transistor base junction (Figs. 1-5*d* and 1-5*e*). An epitaxial layer is grown and a similar process is used to diffuse the

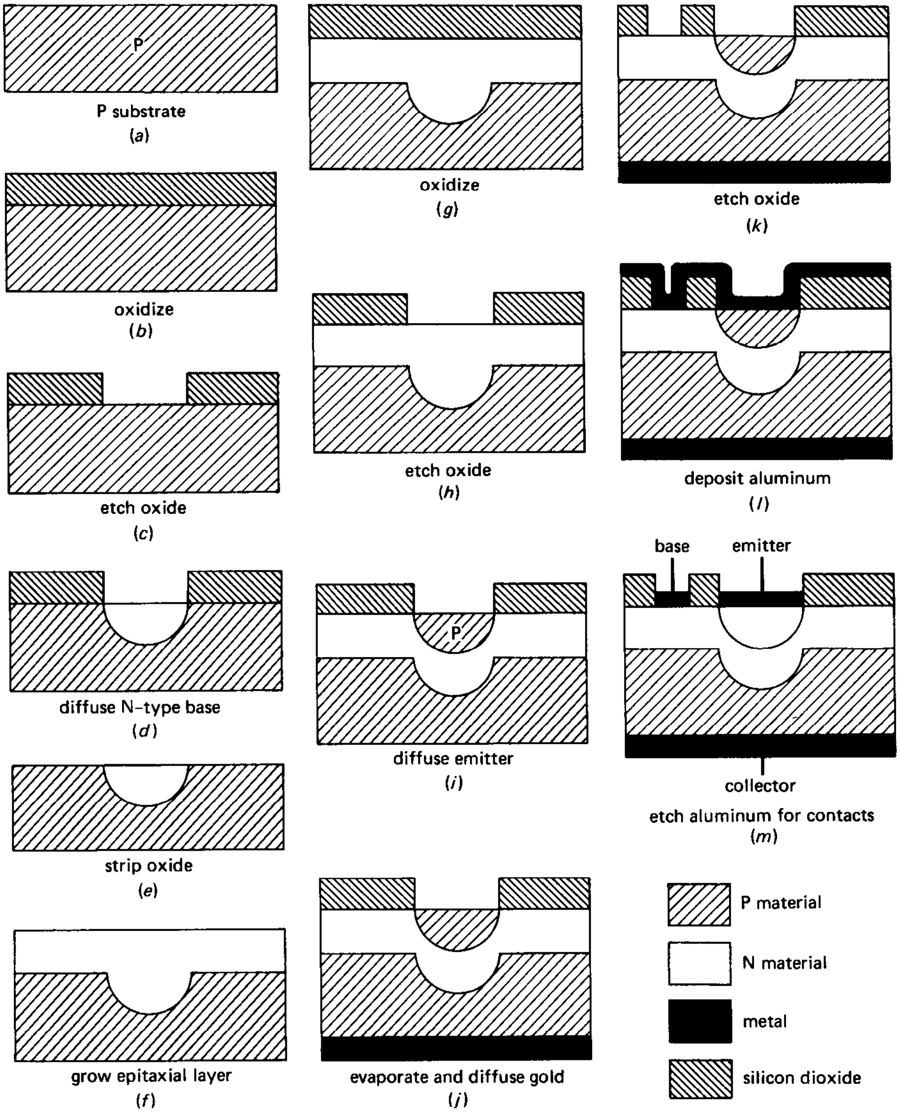


Figure 1-5. Manufacturing a monolithic integrated circuit.

emitter (Figs. 1-5*f* through 1-5*i*). The final steps are used to provide metal contacts for the junction terminals.

Integrated Circuit Review

1. List the advantages of integrated circuits as compared to discrete components.
2. Describe the fabrication methods used in manufacturing integrated circuits.
3. Distinguish between field-effect and bipolar transistors.
4. Describe the various processes used to dope semiconductors with impurities.

PULSE SIGNALS

In your previous study of electronic circuits, you were mostly concerned with dc and ac steady-state signals. While some integrated

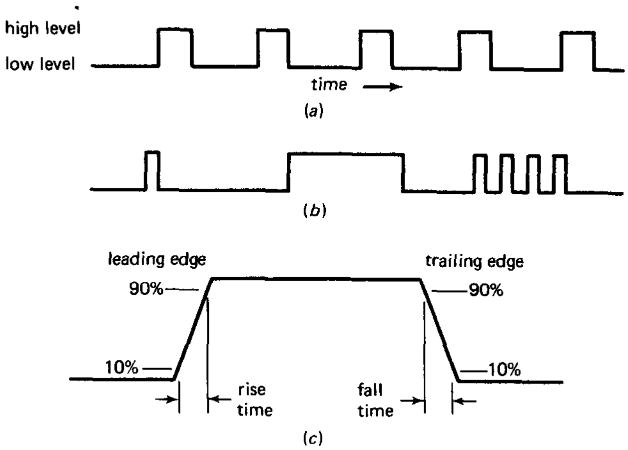


Figure 1-6. Pulse Signals. (a) Periodic, (b) aperiodic, (c) rise and fall time.

circuits use these types of signals, most respond to individual pulses or pulse trains. As Fig. 1-6 shows, the pulses may be spaced at regular intervals or they may arrive at random times. The regular pulses are called *periodic* (Fig. 1-6*a*), while the others are *aperiodic* (Fig. 1-6*b*).

The amplitude of the signal at any time is either at a high- or low-voltage level. Intermediate values are not allowed. The time required for the voltage to rise from 10 percent of the high level to 90 percent of that voltage on the leading pulse edge is called the *rise time*. The *fall time* is the time elapsed while the voltage drops from 90 percent to 10 percent of the high-voltage level on the trailing edge. These values are shown in Fig. 1-6*c*.

Pulse Signal Review

1. Distinguish between periodic and aperiodic pulse signals.
2. Define the terms *rise time* and *fall time*.

CHAPTER SUMMARY

1. The active and passive elements which make up an integrated circuit are inseparable from the substrate. The elimination of discrete transistors, resistors, and capacitors by integrated circuitry results in significant savings in constructing electronic equipment.
2. Advantages of integrated circuits include simplified designs, fewer interconnections, small size, increased speed, low power, and improved reliability.
3. Integrated circuits are fabricated by the monolithic, multichip, film, and hybrid-circuit processes.
4. Bipolar and field-effect transistors are used for integrated circuits. Bipolar transistors are characterized by two adjacent PN junctions.
5. Hybrid circuits require that chips be joined to the thin film by soldering them to a metallized pad or by the inverted assembly or beam lead methods.
6. Pulse signals can be classified as periodic or aperiodic. The transition time between the high and low voltages of the pulses is specified by the rise and fall times.

KEY TERMS AND CONCEPTS

integrated circuit
discrete components
substrate
monolithic integrated circuit
multichip circuit
thin- and thick-film integrated circuits
hybrid integrated circuits
mask
doping
bipolar transistor
field-effect transistor
epitaxial growth
solid-state diffusion
ion implantation
periodic and aperiodic pulses
rise time
fall time

EXPERIMENT 1 INTRODUCTION

The experiments at the end of each chapter will increase your understanding of integrated circuits more than any other section in this book. The experiments have been designed to use a minimum of equipment, yet demonstrate the most popular types of ICs commonly found in the electronic equipment of today. Every attempt has been made to include components which do not require critical values to be selected. For example, circuit operation is generally not sensitive to resistor values, so 10 percent resistors are adequate. Other resistors of approximately the same values can often be substituted without degrading circuit operation. Your instructor may suggest circuit elements equivalent to type shown in the book, or you may wish to try some on your own.

A power supply suitable for TTL operation is required in all experiments. While only low voltage is used in the experiments, 115-volt line voltage is applied to the power supply input, so all electrical safety precautions should be followed. Your instructor will probably explain the guidelines for electrical safety in the laboratory. Check with the instructor if you have any questions before proceeding with any experiment.

TOOLS AND TEST EQUIPMENT

Only common hand tools and a voltmeter are required for these experiments. The suggested tools and meter are:

diagonal cutters
needle-nose pliers
knife
wire stripper
small screwdriver
voltmeter (either VOM or VTVM)

HINTS FOR WORKING WITH TTL

1. All inputs to a TTL integrated circuit must be connected to either an input signal, the power supply, or a ground. If they are allowed to "float," the inputs will rise to a high-level input producing incorrect outputs and will also become excellent sources for introducing noise. You may also be surprised to find that TTL outputs are often much less than +5 volts. A value around 3.3 volts is chosen for real devices to get optimal performance from the design.
2. If you are not familiar with integrated circuit pin numbering, be extra careful to insert the chip with the indicating notch or dot toward the left. When the pins are pointing downward and the notch (or dot) is toward the left, pin 1 is in the left bottom corner of the IC.
3. Use solderless breadboarding systems to build your circuits. ICs and other components snap in place on the board. Remove ICs by gently prying them up with a screwdriver, so the pins are not bent. Sources for breadboarding systems are listed in most electronics periodicals.