Electronics
Principles and Applications

Second Edition

SCHULER

BSEE

C SKILLS IN ELECTRICITY AND ELECTRONICS

ELECTRONICS PRINCIPLES AND APPLICATIONS

SECOND EDITION

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The original, on-site classroom testing of the first editions of books in this series was conducted at the Burr D. Coe Vocational Technical High School, East Brunswick, New Jersey; Chantilly Secondary School, Chantilly, Virginia; Nashoba Valley Technical High School, Westford, Massachusetts; Platt Regional Vocational Technical High School, Milford, Connecticut; and the Edgar Thomson, Irvin Works of the United States Steel Corporation, Dravosburg, Pennsylvania. Postpublication testing was also conducted at Alhambra High School, Phoenix, Arizona; St. Helena High School, St. Helena, California; and Addison Trail High School, Addison, Illinois.

In the years since publication of the first books in this series, research has continued. Thousands of teachers, students, school administrators, and industrial trainers as well as institutions at every academic level from high school through the community college and university have participated.

The publisher and editors gratefully acknowledge the helpful comments and suggestions received from these participants.

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EDITOR'S FOREWORD

The McGraw-Hill *Basic Skills in Electricity and Electronics* series has been designed to provide entry-level competencies in a wide range of occupations in the electrical and electronics fields. The series consists of instructional materials designed especially for the career-oriented student. Each major subject area covered in the series is supported by a textbook, an activities manual, and a teacher's manual. All the materials focus on the theory, practices, applications, and experiences necessary for those preparing to enter their chosen vocations.

There are two fundamental considerations in the preparation of materials for such a series: the needs of the learner and the needs of the employer. The materials in this series meet these needs in an expert fashion. The authors and editors have drawn upon their broad teaching and technical experiences to accurately interpret the needs of the student. The needs of business and industry were verified through questionnaires, surveys, personal interviews, government occupational trend reports, and field studies.

The widespread acceptance of the *Basic Skills in Electricity and Electronics* series and the positive responses from users confirm the basic soundness in content and design of these materials as well as their effectiveness as learning tools. Yet it is natural that in an ongoing series such as this, refinements in pedagogy and technical content constantly take place. Every effort has been made to provide the most up-to-date materials possible. Teachers will find the texts and manuals in each of the subject areas well-coordinated and structured around a framework of modern objectives. Students will find the concepts clearly presented, lucidly illustrated, and relevant to current technology.

The publisher and editor welcome comments from teachers and students using the books in this series.

Charles A. Schuler
Project Editor

FOREWORD

BASIC SKILLS IN ELECTRICITY AND ELECTRONICS

Charles A. Schuler, Project Editor

Books in this series

Introduction to Television Servicing by Wayne C. Brandenburg
Electricity: Principles and Applications by Richard J. Fowler
Instruments and Measurements by Charles M. Gilmore
Introduction to Microprocessors by Charles M. Gilmore
Small Appliance Repair by Phyllis Palmore and Nevin E. André
Electronics: Principles and Applications by Charles A. Schuler
Digital Electronics by Roger L. Tokheim

PREFACE

This introductory text on the principles and applications of electronics is designed for those students who already have a basic understanding of Ohm's law, Kirchhoff's laws, power formulas, schematic diagrams, and electrical components such as resistors, capacitors, and inductors. A knowledge of basic algebra is the only mathematics prerequisite. This book provides an excellent foundation in electronics for those who may need or want to go into the subject in more depth. It also provides entry-level skills and knowledge for a wide range of occupations in electricity and electronics.

This second edition, like the first, combines theory and applications in a logical, well-paced sequence. It is important that a student's first experience in electronics be based on such an approach. This combination of theory and applications first develops an understanding of how electronic circuits and devices function. It then applies function to solve practical problems and develop worthwhile systems. Electronics is a vital and exciting field—the study of it should be the same.

I have taken a practical approach throughout this text. The devices and circuits presented are typical of those used in all phases of electronics. Theory and calculations are the same as those used by practicing technicians. Reference is made to common aids such as parts catalogs and substitution guides.

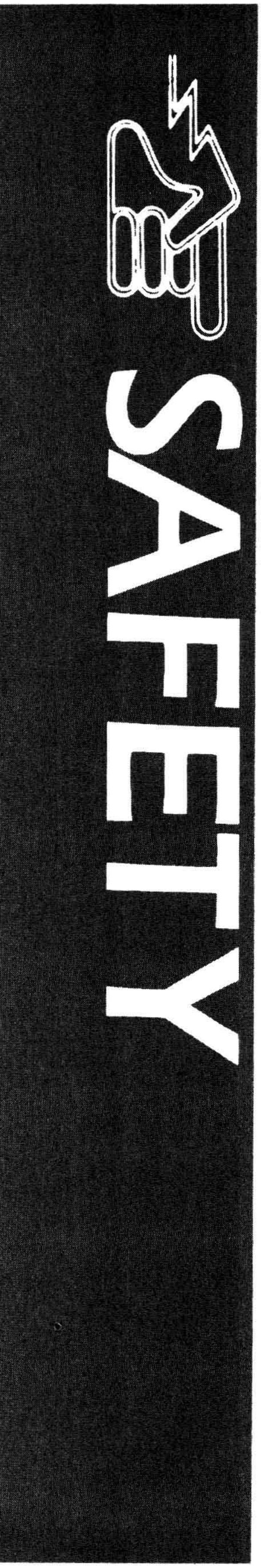
The 15 chapters into which this book is divided progress from an introduction to the field of electronics, through basic solid-state theory, transistors and gain, amplifiers, oscillators, radio, integrated circuits, control circuits, and regulated power supplies. An appendix containing a wide range of BASIC programs, paralleling the text discussions, has been included to serve those students who have access to a microcomputer. While these computer programs will help integrate the traditional text approach with computer use, the availability of a microcomputer is not essential to the effective use of this text.

The development of and approach to each idea and concept have been carefully designed to ensure that students will have a strong foundation on which to build in a field characterized by rapid technological advances. Where appropriate, insights into future trends are also discussed.

This text includes features designed to make the study of electronics more interesting and effective. All important facts and concepts are reviewed in a summary section at the end of each chapter. Students should read these reviews carefully. Any confusion at this point may indicate the need to go back and restudy a section or a portion of the section. Important terms are highlighted in the margins for quick reference. Students will also find review tests after each section and a comprehensive test at the end of each chapter. These will help to ensure adequate comprehension of the material.

I would like to acknowledge all the teachers and students who have used my first edition and provided me with so much invaluable guidance and assistance in preparing this second edition. I also wish to thank those industry personnel who have answered my many questions and shared their vital information with me. As in the past, I welcome comments and suggestions from students and teachers who use this second edition.

Charles A. Schuler



Electric devices and circuits can be dangerous. Safe practices are necessary to prevent electrical shock, fires, explosions, mechanical damage, and injuries resulting from the improper use of tools.

Perhaps the greatest of these hazards is electrical shock. A current through the human body in excess of 10 milliamperes can paralyze the victim and make it impossible to let go of a "live" conductor. Ten milliamperes is a small amount of electrical flow: It is *ten one-thousandths* of an ampere. An ordinary flashlight uses more than 100 times that amount of current! If a shock victim is exposed to currents over 100 milliamperes, the shock is often *fatal*. This is still far less current than the flashlight uses.

A flashlight cell can deliver more than enough current to kill a human being. Yet it is safe to handle a flashlight cell because the resistance of human skin normally will be high enough to greatly limit the flow of electric current. Human skin usually has a resistance of several hundred thousand ohms. In low-voltage systems, a high resistance restricts current flow to very low values. Thus, there is little danger of an electrical shock.

High voltage, on the other hand, can force enough current through the skin to produce a shock. The danger of harmful shock increases as the voltage increases. Those who work on very high-voltage circuits must use special equipment and procedures for protection.

When human skin is moist or cut, its resistance can drop to several hundred ohms. Much less voltage is then required to produce a shock. Potentials as low as 40 volts can produce a fatal shock if the skin is broken! Although most technicians and electrical workers refer to 40 volts as a *low voltage*, it does not necessarily mean *safe voltage*. Obviously, you should, therefore, be very cautious even when working with so-called low voltages.

Safety is an attitude; safety is knowledge. Safe workers are not fooled by terms such as *low voltage*. They do not assume protective devices are working. They do not assume a circuit is off even though the switch is in the OFF position. They know that the switch could be defective.

As your knowledge of electricity and electronics grows, you will learn many specific safety rules and practices. In the meantime:

1. Investigate before you act
2. Follow procedures
3. When in doubt, *do not act*: ask your instructor

General Safety Rules for Electricity and Electronics

Safe practices will protect you and those around you. Study the following rules. Discuss them with others. Ask your instructor about any that you do not understand.

1. Do not work when you are tired or taking medicine that makes you drowsy.
2. Do not work in poor light.
3. Do not work in damp areas.
4. Use approved tools, equipment, and protective devices.
5. Do not work if you or your clothing is wet.
6. Remove all rings, bracelets and similar metal items.
7. Never assume that a circuit is off. Check it with a device or piece of equipment that you are sure is operating properly.
8. Do not tamper with safety devices. *Never* defeat an interlock switch. Verify that all interlocks operate properly.
9. Keep your tools and equipment in good condition. Use the correct tools for the job.
10. Verify that capacitors have discharged. Some capacitors may store a lethal charge for a long time.
11. Do not remove equipment grounds. Verify that all grounds are intact.
12. Do not use adaptors that defeat ground connections.
13. Use only an approved fire extinguisher. Water can conduct electrical current and increase the hazards and damage. Carbon dioxide (CO_2) and certain halogenated extinguishers are preferred for most electrical fires. Foam types may also be used in some cases.
14. Follow directions when using solvents and other chemicals. They may explode, ignite, or damage electrical circuits.
15. Certain electronic components affect the safe performance of the equipment. Always use the correct replacement parts.
16. Use protective clothing and safety glasses when handling high-vacuum devices such as television picture tubes.
17. Do not attempt to work on complex equipment or circuits before you are ready. There may be hidden dangers.
18. Some of the best safety information for electrical and electronic equipment is in the literature prepared by the manufacturer. Find it and use it!

Any of the above rules could be expanded. As your study progresses, you will learn many of the details concerning proper procedure. Learn them well, because they are the most important information available.

Remember, always practice safety; your life depends on it.

CONTENTS

Introduction

CHAPTER 1

The purpose of this chapter is to introduce you to electronics. Electronics is such a huge field that beginners may be confused as to what they are studying. They may also wonder how it relates to what they have already studied.

In this book, *electronics* refers to the study of *active* devices and their uses. An active device is a diode, a transistor, or an integrated circuit. *Passive* devices are resistors, conductors, capacitors, and inductors. Generally, courses that deal mainly with active devices are called electronics courses.

Electronics is really a brand new field. Its entire history is limited to this century. Yet, it has grown so rapidly and become so important that several branches have developed. One of the branches is *digital* electronics. This chapter will define this term and compare it to *analog* electronics. The rapid growth of electronics in recent years will not slow down in the near future. Thus, this chapter will also review some major trends in the field.

1-1 A Brief History

Electronics is very young. It is hard to place an exact date on its beginning. Two important developments at the beginning of this century made people interested in electronics. The first was in 1901 when Marconi sent a message across the Atlantic Ocean using *wireless* telegraphy. Today, we call wireless communication *radio*. The second development came in 1906 when De Forest invented the *audion* vacuum tube. The term "audion" related to its first use to make sounds ("audio") louder. It was not long before the wireless inventors used the vacuum tube to improve their equipment.

There was another development in 1906 worth mentioning. Pickard used the first crystal radio detector. This was a great improvement. It helped to make radio and electronics more popular. It also suggested the use of *semiconductors* (crystals) as materials with great promise for the future of the new field of radio and electronics.

Commercial radio was born in Pittsburgh, Pennsylvania, at station KDKA in 1920. This marked the beginning of a new era with electronic devices appearing in the average home. Commercial television began around 1946. Television receivers were very complex compared to most radios. Other complicated electronic devices were now in use, too. The vacuum tube, which had served so well, was now making engineers and technicians wish for something better.

The first vacuum-tube computer was built in 1943 at the University of Pennsylvania. Soon, commercial vacuum-tube computers became available. They were large and expensive, and generated quite a bit of heat as a result of the many vacuum tubes that they used. They were not very reliable by modern standards. The numerous vacuum tubes and the heat caused many failures. It was not uncommon to have several breakdowns in one day. Television receivers and complex radio receivers had dozens of vacuum tubes, but computers had thousands. Something better than the vacuum tube had to be found.

Scientists knew that many of the jobs done by vacuum tubes could be done more efficiently by semi-conducting crystals. They knew this for quite some time, but they could not make crystals that were pure enough to do the job. They kept working at it. The breakthrough came in 1947. Three scientists working for Bell Laboratories made the first working transistor. This was such a major contribution to science and technology that the three men—Bardeen, Brittain, and Shockley—were awarded the Nobel Prize.

Improvements in the transistor came rapidly, and now transistors have all but completely replaced the vacuum tube. "Solid state" has become a household word. Many people say that the tran-

From page 1:
Audion

Semiconductors

Vacuum tube

Solid state

On this page:
Integrated circuit

Substrate

Microprocessor

Digital electronic device

High or low voltages

Analog circuit

Digital circuits

sistor is one of the greatest developments of all time.

Solid-state circuits were small, efficient, and more reliable. But the scientists still were not satisfied. Nor were the engineers satisfied. So it was with Jack Kilby of Texas Instruments. His work led to the development of the integrated circuit in 1958. Integrated circuits are complex combinations of several kinds of devices on a common base, called a *substrate,* or in a tiny piece of silicon. They offer low cost for the performance, as well as good efficiency, small size, and good reliability. The complexity of some integrated circuits allows a single chip of silicon only 0.64 centimeter (cm) [0.25 inch (in)] square to replace huge pieces of equipment. The chip can hold thousands of transistors. You would not think any room would be left, but you might also find some diodes, resistors, and capacitors too!

In 1971, the Intel Corporation of California announced one of the most sophisticated of all integrated circuits—the microprocessor. A microprocessor is most of the circuitry of a computer reduced to a single integrated circuit. Some modern microprocessors contain the equivalent of 100,000 transistors. Microprocessors have provided billions of dollars worth of growth for the electronics industry and have opened entire new areas of applications.

The integrated circuit is producing an electronics explosion. Now electronics is being applied in more ways than ever before. At one time, radio was just about the only application. Today, electronics makes a major contribution to every part of our society and in every field of human endeavor. It affects us in many ways that we may not even be aware of. We are living in the electronic age.

SELF TEST

Determine whether each statement is true or false.

1. The entire history of electronics is limited to the twentieth century.
2. The early histories of radio and of electronics are the same.
3. Transistors were invented before vacuum tubes.
4. A modern integrated circuit can contain thousands of transistors.

1-2 Digital or Analog

Today, electronics is such a huge field that it is often necessary to divide it into smaller subfields. You will hear terms such as *medical electronics, instrumentation electronics, automotive electronics, avionics, consumer electronics,* and others. One way that electronics can be divided is into *digital* and *analog.*

A digital electronic device or circuit will recognize or produce an output of only several limited states. For example, most digital circuits now in use will respond to only two conditions: high or low voltages. Digital circuits can be built that will operate with more than two states, but most are limited to only two.

An analog circuit can respond to or produce an output of an infinite number of states. An analog voltage might vary between 0 and 10. The actual value might be 1.5, 2.8, or even 7.653 volts (V). In theory at least, an infinite number of voltages are possible.

For a long time, almost all electronic devices and circuits operated in the analog fashion. This seemed to be the most obvious way to do a particular job. After all, most of the things that we measure are analog in nature. Your height, your weight, and the speed at which you travel in an automobile are all analog quantities. Your voice is analog. It contains an infinite number of levels and frequencies. Therefore, if you wanted a circuit to amplify your voice, that is, make it sound louder, your first thought would probably be to use an analog circuit.

Telephone switching and computer circuits forced engineers to explore digital electronics. They needed circuits and devices that could make logical decisions based on certain input conditions. They needed highly reliable circuits that would operate in the same way every time. By limiting the number of conditions or states in which the circuits must operate, the circuits could be made more reliable. An infinite number of states—the analog circuit—was not what they needed.

Digital circuits can do most of the things we once thought of as strictly analog. We can amplify and otherwise process sound with digital circuits. Which way something will actually be done is simply a question of efficiency. Circuit designers choose the best way to do a job while keeping the cost as low as possible.

Analog electronics involves techniques and concepts different from those of digital electronics. In this book, you will be studying analog electronics. However, what you learn about analog electronics will serve as a useful background for later studies of digital electronics.

Figure 1-1 gives some examples of circuit behavior that will help you to identify digital or analog operation. The signal going into the circuit is

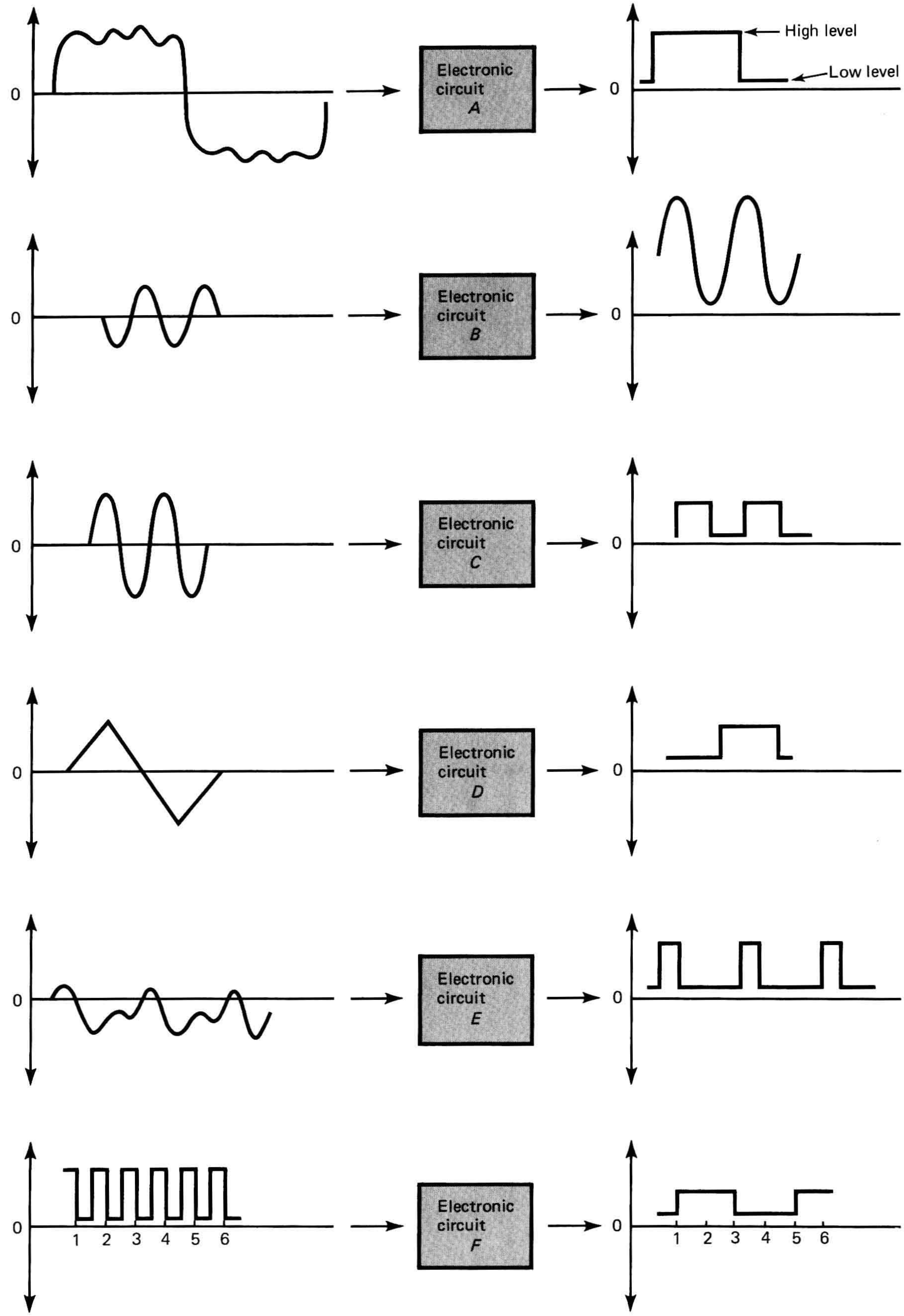


Fig. 1-1 A comparison of digital and analog circuits

Linear circuit

Integrated circuits

Micro-miniaturization

Computer-aided design

Robots

Data bases

Learning curve

on the left, and the signal coming out of the circuit is shown on the right. The circuit marked A is an example of a digital device. The output signal is a square wave while the input signal is not exactly a square wave. Square waves show only *two* voltage levels and are very common in digital devices.

Circuit *B* in Fig. 1-1 is an analog device. The input is a sine wave, and the output is a sine wave. The output is larger than the input, and it has been shifted above the zero axis. The most important feature is that the output signal is a combination of an infinite number of voltages. In a *linear circuit*, the output is an exact replica of the input. Though circuit *B* is linear, *not all analog circuits are linear.*

Circuits C through *F* are all digital. Note that the outputs are all square waves (two levels of voltage). Circuit *F* deserves special attention. Its input is a square wave. This could be an analog circuit responding to only two voltage levels except that something has happened to the signal which did not occur in any of the other examples. The output *frequency* is different from the input frequency. Digital circuits that accomplish this are called *counters*, or *dividers*.

SELF TEST

Determine whether each statement is true or false.

5. Electronic circuits can be divided into two categories, digital and analog.
6. A digital circuit can respond to an infinite number of conditions.
7. Digital circuits became popular before analog circuits.
8. This book is limited to the study of analog circuits.
9. A linear circuit can be put in the digital category.

1-3 Trends in Electronics

Trends in electronics are characterized by enormous growth and by sophistication. The growth is largely the result of "the learning curve" and of healthy competition. The learning curve simply means that as more and more experience is gained, more and more efficiency results. Electronics is maturing as a technology. The yield of integrated circuits is a perfect example of this phenomenon. A new integrated circuit, especially if it is a sophisticated one, may have a yield of less than 10 percent. Nine out of ten devices will not pass the test and must be thrown away. This makes the price of a new device very high. Later, much is learned about making that particular part. The yield goes up to 90 percent. The price drops drastically and many new applications are found for the part because it is now economically attractive to use it. The new parts are complex, powerful, and sophisticated. But their very complexity usually results in a product that is easier to use. In fact, "user friendly" is a term used to describe sophisticated products.

Not only is electronics growing rapidly, it is also changing rapidly. Those who work in electronics must be willing to accept this rapid change. They must be willing to constantly improve themselves and learn more about electronics and how it interacts with other technologies. It will be very challenging and exciting for those involved.

The integrated circuit is the key to most electronic trends. These marvels of micro-miniaturization keep expanding in performance and usually decrease the cost of electronics products. They also mean less energy consumption, they offer high reliability, they are small, and they are light. Is it any wonder that they have stimulated tremendous growth?

That very special integrated circuit, the microprocessor, has brought automation and programmability within the reach of almost everyone. For example, electronic games and video games are microprocessor-based designs. The modern office has become an electronic office. The typewriter is now a word processor. The filing cabinet has been replaced by a spinning magnetic disk. And in the very near future, digital telecommunications systems will make the office hum with an efficient inflow and outflow of information in electronic form.

Industry is now making increasing use of electronic technology to increase productivity. Computer-aided design improves quality and greatly decreases the time to develop new products. Computer-aided manufacturing also increases quality and drastically cuts costs. Robots are eliminating dangerous, physically difficult, and boring jobs. In fact, the industrial robot will eliminate most production jobs by the turn of the century. Will this increase unemployment? Yes, for unskilled and certain semiskilled workers. However, it will create many new jobs for those workers with modern educations. It is often said and written that many future jobs are not yet identified.

Homes are changing too. The automatic appliances are giving way to computerized and programmable appliances. There are more kinds of equipment for entertainment and education in the home. Home computers are popular, and many home computers are tapping into large data bases by connecting to them through the telephone lines. Homes now have smoke detectors, security systems, and systems that result in savings on utility bills. Just think how many "electronic gadgets" that are around today did not exist just a few short years ago.

Schools use computers to keep records and assist in the educational process. Students learn about computers and they learn from them. Doctors use computers to help diagnose patients. Sophisticated computerized scanners even let the doctors "see" inside a patient's body without resorting to surgery. Other electronic devices can block pain, regulate certain body functions, and actually keep some patients alive.

The automobile is becoming an electronics package. Microprocessors regulate timing and fuel flow to increase efficiency and decrease pollution. They can also determine the shift points in an automatic transmission and prevent skids due to locked braking systems. Very informative dashboard displays are planned for future models. The driver will be well informed as to speed, distance, and vehicle performance, and will even receive messages when service is required.

The outlook is very bright for those with careers in electronics. The new products, the new applications, and the tremendous growth all mean good jobs for the future. The jobs will not be easy ones. They will be challenging and they will be marked by constant change.

SELF TEST

Determine whether each statement is true or false.

10. Integrated circuits will be used less in the future.
11. The learning curve makes electronic devices less expensive as time goes on.
12. Automation and robotics will eliminate some jobs and create new ones that demand more technical education.

Summary

1. Electronics is a young field. Its entire history is contained in the twentieth century.
2. The key developments in electronics have been
   - 1901 radio
   - 1906 vacuum tube
   - 1947 transistor
   - 1958 integrated circuit
   - 1971 microprocessor
3. Electronic circuits can be classified as digital or analog.
4. The number of states or voltage levels is limited in a digital circuit (usually to two).
5. An analog circuit has an infinite number of voltage levels.
6. In a linear circuit, the output signal is a replica of the input.
7. All linear circuits are analog, but not all analog circuits are linear.
8. Digital circuits will find many new applications and in areas now thought of as analog.

CHAPTER REVIEW QUESTIONS

Determine whether each statement is true or false.

1-1. Radio was invented in 1854.
1-2. Integrated circuits contain several vacuum tubes.
1-3. "Solid state" means that the equipment uses vacuum tubes.
1-4. Most digital circuits can output only two states, high and low.
1-5. Digital circuit outputs are usually sine waves.
1-6. The output of a linear circuit is an exact replica of the input.
1-7. Linear circuits are classified as analog.
1-8. All analog circuits are linear.
1-9. Because of electronics, many future devices will be automatic and programmable.
1-10. Future applications of electronics will be limited to just a few areas in engineering.

Answers to Self Tests

1. T	5. T	9. F
2. T	6. F	10. F
3. F	7. F	11. T
4. T	8. T	12. T

CHAPTER 2

Semiconductors

After a brief review of conductors and insulators you are going to study materials with properties that fall between conductors and insulators. These materials are called *semiconductors.*

Semiconductors have a unique way of supporting the flow of electric current. Some of the current carriers are *not* electrons. High temperatures can create new carriers in semiconductors. These are important differences between semiconductors and conductors.

The transistor has been called one of the most important developments of all time. It is a semiconductor device. To make your study of electronics more effective, you will learn some of the properties of semiconductors.

2-1 Conductors

Conductors are the fundamental component of electronic circuits and devices. They easily and efficiently allow the flow of electric charges. Figure 2-1 shows how a copper wire supports the flow of electrons. A copper atom contains a positively charged nucleus and negatively charged electrons that orbit around the nucleus. Figure 2-1 is simplified to show only the outermost orbiting electron, the *valence electron*. The valence electron is very important since it acts as the *current carrier* for the atom.

Even a very small wire will contain billions of atoms, each with one valence electron. These electrons are only *weakly* attracted to the nucleus of the atom. They are very easy to move. If an electromotive force (a voltage) is applied across the wire, the valence electrons will respond to this force and begin drifting toward the positive end of the source voltage. Since there are so many valence electrons and since they are so easy to move, we can expect tremendous numbers of electrons to be set in motion by even a small voltage. Thus, we say copper is an excellent electric conductor. We can also say that is has *low resistance*.

Heating the wire will change its resistance. As the wire becomes warmer, the valence electrons become more active. They move farther away from the nucleus, and they move more rapidly. This increases the chance for collisions as the electrons drift toward the positive end of the wire. These collisions resist the current. Therefore the resistance of the wire is a little greater than it was before.

All conductors show this effect. As they become

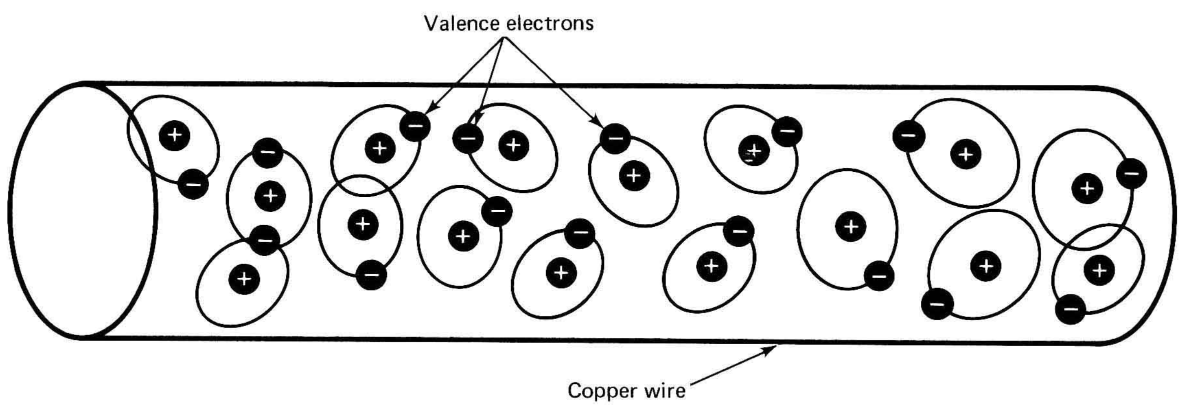


Fig. 2-1 The structure of a copper conductor

hotter, they conduct less efficiently and their resistance increases. Such materials are said to have a *positive temperature coefficient.* This simply means that the relationship between temperature and resistance is positive—that is, they increase together.

Copper is the most important conductor in electronics. Almost all the wire used in electronics is made from copper. Printed circuits use copper foil to act as circuit conductors. Copper is a good conductor, and it is easy to solder. This makes it very popular.

Silver is the best conductor because it has the lowest resistance. It is also easy to solder. The cost of silver makes it less popular than copper. However, silver-plated conductors are sometimes used in critical electronic circuits to minimize resistance.

Gold is a good conductor. It is very stable and does not corrode as badly as copper and silver. Sometimes sliding and moving electronic contacts will be gold-plated. This makes the contacts very reliable.

SELF TEST

Determine whether each statement is true or false.

1. Valence electrons are located in the nucleus of the atom.
2. In conductors, the valence electrons are strongly attracted to the nucleus.
3. The current carriers in conductors are valence electrons.
4. Cooling a conductor will decrease its resistance.
5. Silver is not often used in electronic circuits because of its high resistance.

2-2 Semiconductors

Semiconductors do not allow current to flow as easily as conductors do. Under some conditions semiconductors can conduct so poorly that they behave as insulators.

Silicon is a very popular semiconductor. It is used to make diodes, transistors, and integrated circuits. These and other components make modern electronics possible. It is very important to understand some of the details about silicon.

Figure 2-2 shows atomic silicon. The compact bundle of particles in the center of the atom contains protons and neutrons. This bundle is called the *nucleus* of the atom. The protons show a positive (+) electric charge, and the neutrons show

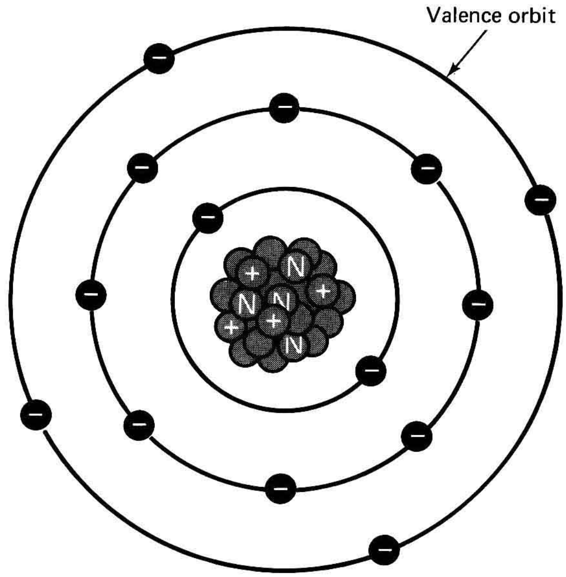


Fig. 2-2 The structure of a silicon atom

no electric charge (N). Negative electrons travel around the nucleus in *orbits*. The first orbit has two electrons. The second orbit has eight electrons. The last, or outermost, orbit has four electrons. The outermost orbit is the most important atomic feature when you are studying the electrical behavior of materials. It is called the *valence orbit.*

Because we are interested mainly in the valence orbit, it is possible to simplify the drawing of the silicon atom. Figure 2-3 shows only the nucleus and the valence orbit of a silicon atom. Remember that there are four electrons in the valence orbit.

Materials with four valence electrons are not stable. They tend to combine chemically with other materials. They can be called *active* materi-

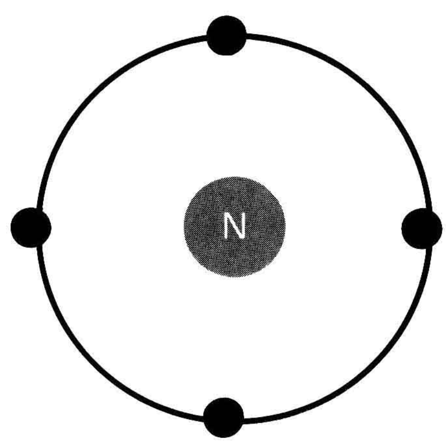


Fig. 2-3 A simplified silicon atom

On page 6:
Conductors

Electrons

Copper atom

Valence electron

Current carrier

Electromotive force (a voltage)

Low resistance

On this page:
Positive temperature coefficient

Printed circuits

Semiconductors

Silicon

Diodes

Transistors

Protons

Neutrons

Nucleus of the atom

Orbits

Valence orbit

Active materials

Silicon dioxide

Ionic bond

Covalent bonding

Crystal

Insulators

Negative temperature coefficient

Germanium

als. This activity can lead them to a more stable state. A law of nature makes certain materials tend to form combinations that will make *eight* electrons available in the valence orbit. Eight is an important number because it gives stability.

One possible combination for silicon is with oxygen. A single silicon atom can join, or link, with two oxygen atoms to form silicon dioxide. This linkage is called an *ionic bond*. The new structure is much more stable than either silicon or oxygen. It is interesting to note that chemical, mechanical, and electrical properties often run parallel. Silicon dioxide is stable chemically. It does not react easily with other materials. It is stable mechanically. It is a hard, glasslike material. It is stable electrically. It does not conduct; in fact, it is used as an insulator in integrated circuits and other solid-state devices.

Sometimes oxygen or any other material is not available for silicon to combine with. The silicon still wants the stability given by eight valence electrons. If the conditions are right, silicon atoms will arrange to *share* valence electrons. This process of sharing is called *covalent bonding*. The structure that results is called a *crystal*. Figure 2-4 is a symbolic diagram of a crystal of pure silicon. The dots represent valence electrons.

Count the valence electrons around the nucleus of one of the atoms shown in Fig. 2-4. Select one of the internal atoms as represented by the circled N. You will count *eight* electrons. Thus, the silicon crystal is very stable. At room temperature, *pure silicon is a very poor conductor*. If a moderate voltage is applied across the crystal, very little current will flow. The valence electrons that normally would support current flow are all tightly locked up in covalent bonds.

Pure silicon crystals behave as insulators. Yet they are classified as semiconductors. They can be made to semi-conduct. One way to do this is to heat them. Heat adds energy to the crystal. An electron can absorb some of this energy and move to a higher orbit level. The high-energy electron will break its covalent bond. Figure 2-5 shows a high-energy electron in a silicon crystal. This electron is free to move and will serve as a current carrier. Now, if a voltage is placed across the crystal, current will flow.

Silicon has a *negative temperature coefficient*. As temperature increases, resistance decreases in silicon. It is difficult to predict exactly how much the resistance will change in a given case. One rule of thumb is that the resistance will be cut in half for every 6° C rise in temperature.

The semiconductor *germanium* is used to make transistors and diodes, too. Germanium has four valence electrons and can form the same type of crystalline structure as silicon. It is interesting to observe that the first transistors were all made of germanium. The first silicon transistor was not developed until 1954. Now, silicon has almost replaced germanium in most solid-state applica-

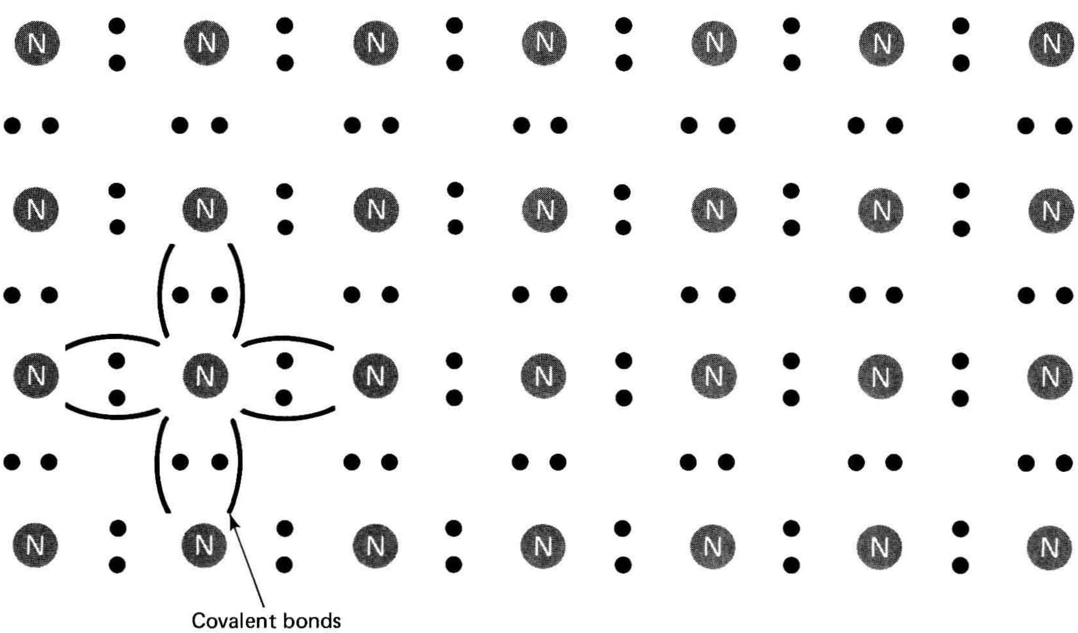


Fig. 2-4 A crystal of pure silicon

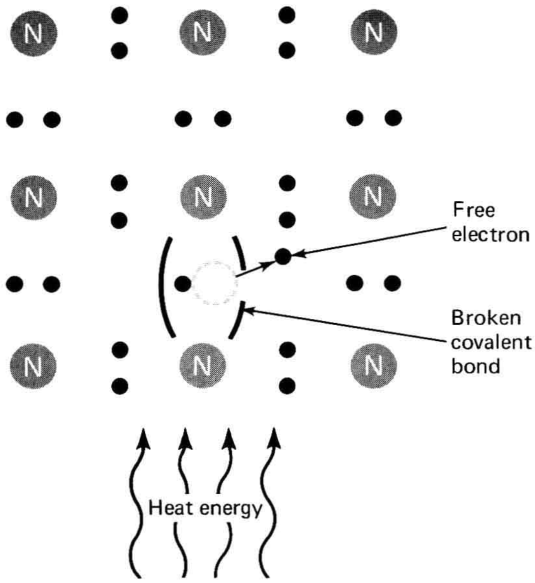


Fig. 2-5 Thermal carrier production

tions. One of the major reasons for this shift from germanium to silicon is the temperature response. Germanium also has a negative temperature coefficient. The rule of thumb for germanium is that the resistance will be cut in half for every 10°C rise in temperature. This would seem to make germanium more stable with temperature change.

The big difference between germanium and silicon is the amount of heat energy needed to move one of the valence electrons to a higher orbit level, breaking its covalent bond. This is far easier to do in a germanium crystal. A comparison between two crystals, one germanium and one silicon, of the same size and at room temperature will show about a 1000:1 ratio in resistance. The silicon crystal will actually have 1000 times the resistance of the germanium crystal. So even though the resistance of silicon changes more rapidly with increasing temperature than that of germanium, silicon is still going to show greater resistance than germanium.

It is easy to see why circuit designers prefer silicon devices for most uses. The thermal, or heat, effects are usually a source of trouble. Temperature is not easy to control, and we do not want circuits to be influenced by it. However, all circuits are changed by temperature. Good designs minimize that change.

Sometimes heat-sensitive devices are necessary. A probe for measuring temperature might take advantage of the temperature coefficient of semiconductors. So the temperature coefficient of semiconductors is not always a disadvantage.

Determine whether each statement is true or false.

6. Silicon is a conductor.
7. Silicon has four valence electrons.
8. Silicon dioxide is a good conductor.
9. A silicon crystal is formed by covalent bonding.
10. A pure silicon crystal acts as an insulator at room temperature.
11. Heating semiconductor silicon will decrease its resistance.
12. Semiconductor germanium has less resistance than semiconductor silicon.
13. Silicon transistors and diodes are not used as often as germanium devices.

2-3 N-Type Semiconductors

Thus far, we have seen that pure semiconductor crystals are very poor conductors. High temperatures can make them semi-conduct because carriers are produced. There has to be another way to make them semi-conduct.

Doping is a process of adding other materials to the silicon crystal to change its electrical characteristics. One such doping material is arsenic. Figure 2-6 shows a simplified arsenic atom. Arsenic is different from silicon in several ways, but the important difference here is in the valence orbit. Arsenic has five valence electrons.

When an arsenic atom enters a silicon crystal, a free electron will result. Figure 2-7 shows what happens. The covalent bonds will capture four of the arsenic atom's valence electrons, just as if it were another silicon atom. This tightly locks the arsenic atom into the crystal. The fifth valence

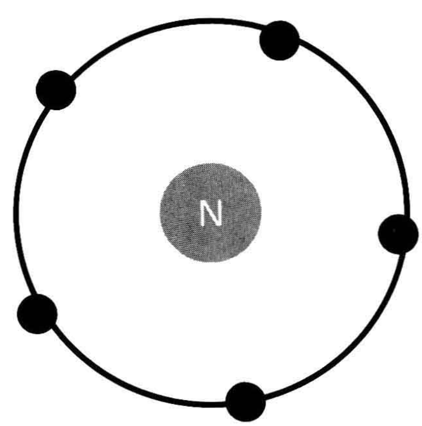


Fig. 2-6 A simplified arsenic atom

Temperature response

Doping

Arsenic