solid state electronic circuits: for engineering technology

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SOLID STATE ELECTRONIC CIRCUITS: FOR ENGINEERING TECHNOLOGY

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preface

This book discusses basic semiconductor circuits, including the physical operation and electrical characteristics of the more common solid state devices.

The level should be suitable for engineering technology curricula in junior and community colleges as well as training programs in industry and government. The practicing technician or engineer may also find the book useful as a refresher or reference.

Abbreviations for units and prefixes conform to IEEE (Institute of Electrical and Electronics Engineers) Standard No. 260. A list is given in Appendix 1. Letter symbols for electrical quantities and parameters generally conform to IEEE Standard No. 255. Conventional current flow is used throughout the book; this convention, as well as graphic symbols for voltage and current sources, is illustrated in Appendix 2.

The content is both qualitative and quantitative; simple design is used wherever feasible. The mathematical level is limited to basic algebra and trigonometry. Although the student should have had or be taking concurrently a course in electric circuits (passive), a review is provided, along with illustrative examples, in the appendices. This review covers voltage and current dividers, loop and node analysis, determinants, complex numbers, Thevenin and Norton equivalent circuits, power transfer between source and load, and superposition. Some derivations requiring the use of calculus are carried out in Appendix 11.

Information from manufacturers' data sheets is used throughout the book; a number of representative data sheets are reproduced in Appendix 10. References are given at the end of each chapter to other books and publications dealing with the specific content of that chapter in greater depth. The book includes a large number of examples and problems. Problem sets generally appear at the end of individual sections in each chapter. Thus the student knows when he can tackle the problems and obtains the benefits of immediate reinforcement.

Chapter 1 develops properties of the PN junction as a starting point for the understanding of diodes and transistors.

The diode as an ideal and real device is treated in Chap. 2. In addition to diode familiarization, the purpose of this chapter is to introduce analytic techniques for later application. Characteristic curves, model construction, load line analysis, and large-signal versus small-signal operation are some of the topics treated. The diode's relative simplicity makes the introduction of these concepts simpler than with active devices.

Applications of diodes are discussed in Chap. 3. These include basic rectifier and power supply circuits, as well as Zener diode voltage regulators and clipping and clamping circuits. Diode models from the previous chapter are utilized to solve problems.

Chapter 4 introduces the amplifier as a black box. Performance measures are defined for amplifiers regardless of the active device used. The concepts and analysis techniques therefore apply to any type of amplifier, using discrete components or integrated circuits. The material should be of interest to anyone who needs to know about the external performance of amplifiers but is not concerned with their internal operation. In addition to basic performance measures, such as amplification, gain, and impedance levels, the topics of frequency response, distortion, and noise are also introduced. Bode plots are presented and extensively used. The concepts of *source* and *load* are treated under "Transducers," giving typical examples. The material in this chapter can be covered entirely before active devices are discussed, or it can be used as a reference while studying active circuits. The advantage of this approach is that, when circuits are later introduced, the student is already familiar with performance criteria and can better appreciate the reasons for using various circuit configurations. The student who is not concerned with the internal behavior of amplifiers can bypass Chaps. 5 through 9 and go directly to Chaps. 10 and 11 ("Feedback" and "DC Circuits").

Chapters 5 through 8 deal with junction (bipolar) transistors. Applications here are limited to small signals and low frequencies; however, static switching behavior is also discussed. The operation, characteristics, ratings, and manufacturing techniques, including the use of data sheets, are presented along with graphic and equivalent circuit analysis methods.

Chapter 9 discusses field effect transistors (FETs). The physical structure, operation, and electrical characteristics (static and dynamic) are treated. The various amplifier configurations are analyzed, including high-input impedance techniques and frequency response.

Feedback as a tool for improving amplifier performance and for system control is presented in Chap. 10. Stability considerations are discussed, including Nyquist's criterion. Many of these concepts are applied in Chap. 11 ("DC Circuits") in conjunction with differential and operational amplifiers as well as with transistorized voltage regulators.

Large-signal amplifiers are covered in Chap. 12. Output power, distortion, efficiency, and thermal considerations, including heat sinks, are emphasized. Class B circuits are treated in some detail, leading to complementary symmetry configurations.

Chapter 13 considers RF circuits, including some background indicating their application in communication systems. y parameters are developed and applied to the analysis of field effect and bipolar transistor circuits. Many RF circuits require extensive alignment "on the bench"; hence a lot of emphasis is placed on tuned circuits and impedance transformation techniques. Stability through neutralization, unilateralization, and mismatching is discussed. Frequency spectra, as well as filtering concepts, are developed in conjunction with class C amplifiers, frequency multipliers, and mixers. AGC techniques for both FETs and bipolar transistors are also covered.

Oscillators of the harmonic and relaxation type are treated in Chap. 14. Concepts and techniques from Chaps. 10 and 13 are used to develop the theory and methods of analysis. Active devices used are the bipolar, field effect, and unijunction transistors, as well as tunnel diodes. The basic *RC*, Colpitts, Hartley, and Clapp configurations are analyzed using techniques appropriate to each specific circuit. The problems of frequency stability are introduced, leading to a discussion of crystal-controlled oscillators.

Chapter 15 deals with pulse circuits. Pulse parameters are defined, and pulse shaping in terms of linear and nonlinear processing is discussed. Compensated voltage dividers, linear inverters, and differentiating and integrating circuits represent the first part. The switching characteristics of bipolar and field effect transistors as well as SCRs are then presented, leading to nonlinear circuits. These include the monostable multi, the Schmitt trigger, step and sweep generators, SCR control circuits, and the flip-flop, including triggering techniques.

Many persons and organizations have contributed to the development of this book. The author is grateful to the manufacturers and publishers who have granted permission to use various illustrations and data sheets. The suggestions of many reviewers have been incorporated throughout the book. Special thanks go to D. Roddy, J. Coolen, and D. McLean (Lakehead University); G. M. Mitchell (Spokane Community College); G. Schickman (Miami Dade Junior College); N. Wipond (Sir Sandford Fleming College); I. Morgulis, G. Martinson, M. Ghorab, and C. Barsony (Ryerson Polytechnical Institute); J. Kendall (University of Alberta, Calgary); M. Anderson, S. Stewart, D. Ropchan, D. Driscoll, and L. Ozbolt (Confederation College). Last, but not least, I should like to acknowledge my wife's extreme patience in enduring for so long the hardships inherent in the preparation of this work.

A. S. Manera

contents

APPENDIX

chapter 1

basic properties of semi-conductors

1.1 INTRODUCTION

Solid state devices, whose study we propose to undertake, are the basic building blocks of modern electronics. In addition to increased reliability, smaller size, lower power consumption, and other advantages over vacuum tubes, solid state devices have often been responsible for the simplification of complex circuitry needed to perform various functions.

Before we attempt to discuss the characteristics of these devices, however, a brief review of the fundamentals of atomic theory will be worthwhile.

The existence of matter is relatively obvious; matter is the stuff around us, it takes up space. The concept of *charge,* however, is often a stumbling block to an understanding of certain physical phenomena. Yet matter and charge are very real quantities, intimately working together to make up the world around us.

Charge is related to force; it is, in fact, a concept invented to explain the existence of certain forces. The fact that solids actually exist implies the presence of forces. Since great pressure is required to compress a solid block of steel, there must be repulsive forces acting inside the steel; similarly, if we try to tear the block apart, the existence of strong attractive forces becomes evident. The theory which uses the concept of charge goes a long way toward explaining these forces of attraction and repulsion.

Although there are different kinds of matter, the basic particles are the same. These are electrons, protons, and neutrons. All three are needed to make up the atom, which is the smallest distinguishable unit of different kinds of matter. We know of about 100 different kinds of atoms, each involving a different arrangement of electrons, protons, and neutrons. Each different atom represents a different element, unique in its characteristics as observed by external experiments. Iron, copper, hydrogen, silver, and gold are examples of elements. Each of these elements contains only one kind of atom. An atom of iron differs from an atom of copper only in the number and arrangement of the basic particles. Different elements can also be chemically combined; in this case the resulting substance is called a compound.

An atom resembles our solar system in that it appears to be made up of a central core, or *nucleus*, around which electrons continuously rotate. The nucleus contains protons and neutrons. Neutrons have no electrical property of interest to us, but electrons and protons do. Protons have about 2,000 times the mass of electrons; neutrons have essentially the same mass as protons. The distinguishing feature of greatest importance, however, is the electric *charge* associated with each of these particles. Electrons appear to be repelled by other electrons and attracted to protons. The physical property responsible for these effects of attraction and repulsion is what we call charge. The unit of measurement for charge is the coulomb, abbreviated as C.[1] The charge on electrons is arbitrarily called negative, while that on protons is positive. The magnitude of charge on either the electron or proton is approximately 1.6×10^{-19}C. A neutron has no charge.

Electrons rotate around the nucleus of their atoms in specific energy levels. Energy is required to move electrons away from the nucleus; thus electrons closest to the nucleus have less energy than those farthest from the nucleus, as shown graphically in Fig. 1.1. Energy is measured in electron volts (eV), where one electron volt is the energy required to move one electron across a potential difference of one volt.

Substances are formed by the *bonding* of many atoms. When atoms are bonded, the individual energy levels of electrons merge into *bands* of allowable energy states. Separating these bands are energy gaps, or forbidden energy bands. These are energy levels in which no electron can exist. Exciting the atom—that is, adding energy to it—may result in electrons overcoming the energy gap and moving into a band further from the nucleus.

The outermost energy band of an unexcited atom is the valence band. If energy is added to the atom, electrons may be boosted to the conduction band, where they are relatively free and can move about the material without being associated with any particular atom. Figure 1.2 depicts the valence and

[1] See Appendix 1 for a list of units and their standard abbreviations.

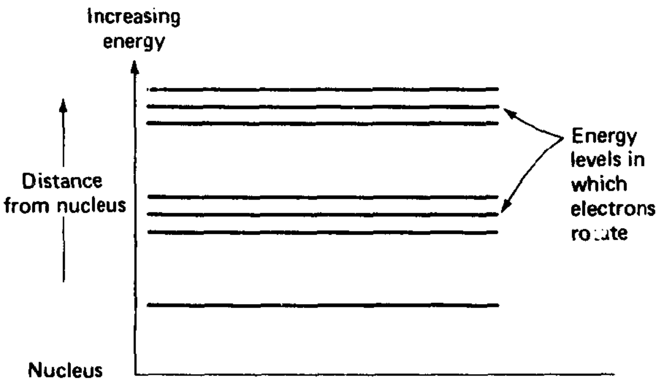

Fig. 1.1 Electrons in a single atom orbit the nucleus in specific energy levels; energy increases as we move further away from the nucleus.

conduction bands, as well as the energy gap separating them. An atom that has more or fewer electrons than its normal complement is said to be ionized. In the case of an electron loss, the atom is a positive ion; if electrons have been gained, it is a negative ion.

The energy gap between valence and conduction bands is an important measure of how materials behave electrically. Certain materials are characterized by a wide energy gap. This implies that valence electrons cannot be boosted to the conduction band unless a relatively large amount of energy is applied. These materials are electric insulators. On the other hand, elements for which the conduction and valence bands overlap are electric conductors. Here conduction electrons are readily available.

Somewhere between these extremes lie elements for which the energy gap between valence and conduction bands is intermediate to insulators and

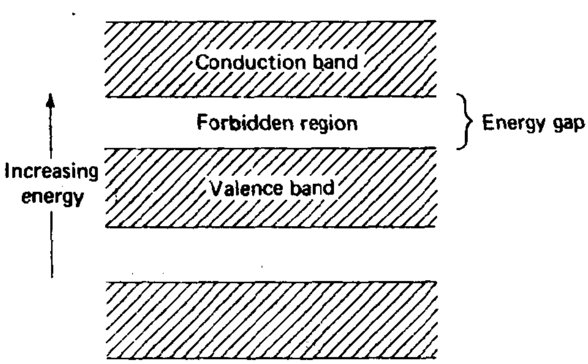

Fig. 1.2 The forbidden region represents a discrete energy gap that must be overcome before valence electrons can reach the conduction band.

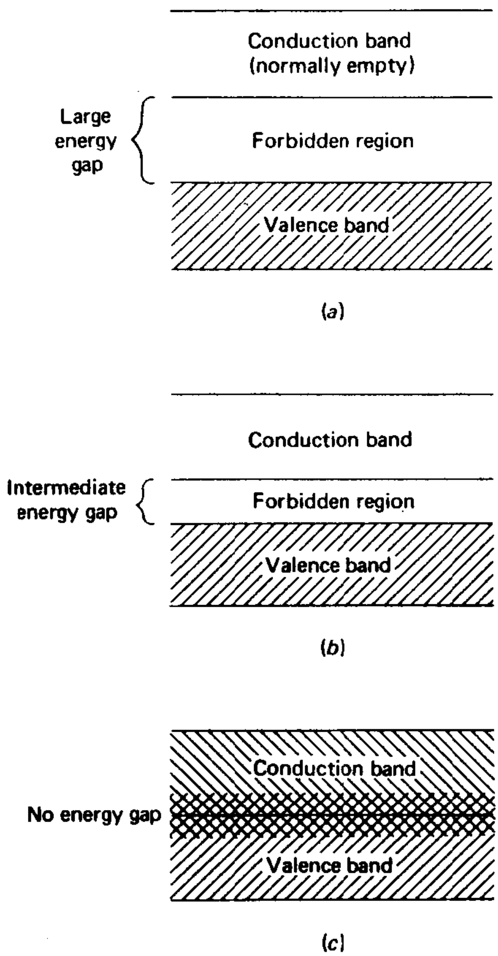

Fig. 1.3 Classification of the electrical properties of materials according to the width of energy gap between valence and conduction bands: (a) *insulators;* (b) *semiconductors;* (c) *conductors.*

conductors. These elements are semiconductors. Figure 1.3 illustrates the relationship between energy gap and electrical properties of materials.

Although several different materials behave as semiconductors, there are two which have found the greatest application. These are the elements silicon and germanium (Si and Ge), both of which have four valence electrons. Elements such as carbon and compounds such as gallium arsenide (GaAs) may also be used, but due to practical difficulties silicon and germanium continue to dominate.

Both Si and Ge atoms are arranged in a crystalline structure. This is a three-dimensional structure, characteristic of most solids, that involves an orderly and repetitive arrangement of atoms. Practical semiconductor devices are manufactured using single continuous crystals; that is, throughout the sample, the orderly arrangement of atoms keeps repeating itself without any abrupt changes. When more than one crystal is involved (polycrystalline materials), irregularities at crystal boundaries affect electrical performance in a manner that is difficult to predict and control.

The four valence electrons associated with each Si or Ge atom form pairs of electrons with neighboring atoms, as shown in the simplified two-dimensional view of Fig. 1.4. Here valence electrons are "shared" among neighboring atoms, so that each atom appears to have not four, but eight valence electrons. The motion of these valence electrons produces attractive forces that bind the various atoms in a specific crystal structure. These attractive forces represent a bond, appropriately called a covalent bond.

Covalent bonds involve electrons from the valence band which are not free charge carriers. If one were to apply enough energy, however, the covalent bond could be broken, and the electrons would move to the conduction band, where they would be free to carry an electric current. The energy required to break the bond could come from heat, light, or an electric field.

A pure semiconductor in which all valence electrons form covalent bonds is an insulator. Here energy levels in the conduction band are empty, or unfilled. At room temperature, however, enough heat energy is present to break some covalent bonds. Thus many free electrons are usually available. If, however, the semiconductor is cooled to a temperature of absolute zero, there is no heat energy, and all electrons form covalent bonds (unless some other form of energy is supplied). In this case, the material does not conduct.

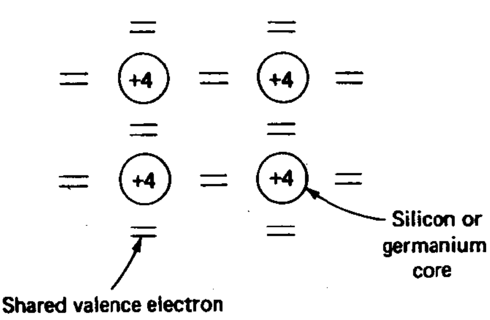

Fig. 1.4 Covalent bond structure for silicon or germanium; simplified two-dimensional representation. Each electron has a negative charge; the shared electrons form a covalent bond. All 32 protons and 28 electrons are included in the Si or Ge core. The remaining four valence electrons are shown separately to illustrate covalent bonding. The core has a net charge of +4, while the valence electrons have a net charge of −4. Therefore the total charge for each atom is zero.

Problem Set 1.1

1.1.1. Why is the concept of charge useful?
1.1.2. Is an electron which is far from the nucleus of its atom at a higher or lower energy level than an electron which is closer to the nucleus?
1.1.3. What two energy bands in atoms are of greatest importance to the study of semiconductors?
1.1.4. When is an atom ionized?
1.1.5. Are electrons in the valence band normally "free"?
1.1.6. When would an electron from the valence band move to the conduction band?
1.1.7. How does the energy gap between valence and conduction bands determine the electrical properties of a material?
1.1.8. What is a covalent bond?
1.1.9. If no external source of energy is available, will a pure semiconductor such as germanium or silicon be capable of electric conduction?
1.1.10. Does the electric resistance of a semiconductor bar depend on temperature? If so, in what way?

1.2 INTRINSIC CONDUCTION

A semiconductor without any impurities is an *intrinsic* semiconductor. Any electric conduction that may take place in such a material is called intrinsic conduction.

You will recall that, at room temperature, some covalent bonds are broken because of the presence of heat. As this happens, electrons from the broken covalent bond move into the conduction band, where they move randomly around the crystalline structure. If an external voltage is applied, these electrons flow, resulting in current.

When an atom loses a valence electron, an incomplete covalent bond results. The missing valence electron is called a *hole*. The hole is a positive-charge carrier, since it is due to the absence of a negatively charged particle (valence electron). Even though a hole is not a particle, its positive charge can move, resulting in an electric current.

Suppose that a valence electron manages to move into a hole. Since it has been filled by an electron, the hole is no longer there. In this case recombination has taken place—that is, the hole has been neutralized. The electron which fills this hole, however, has left a vacancy in its original covalent bond. In effect, a hole has now appeared there. We can say either that the valence electron moved to fill the hole or that the hole moved to where the valence electron used to be. Figure 1.5 illustrates the sequence of events.

Why must we consider the hole concept at all when we could talk only