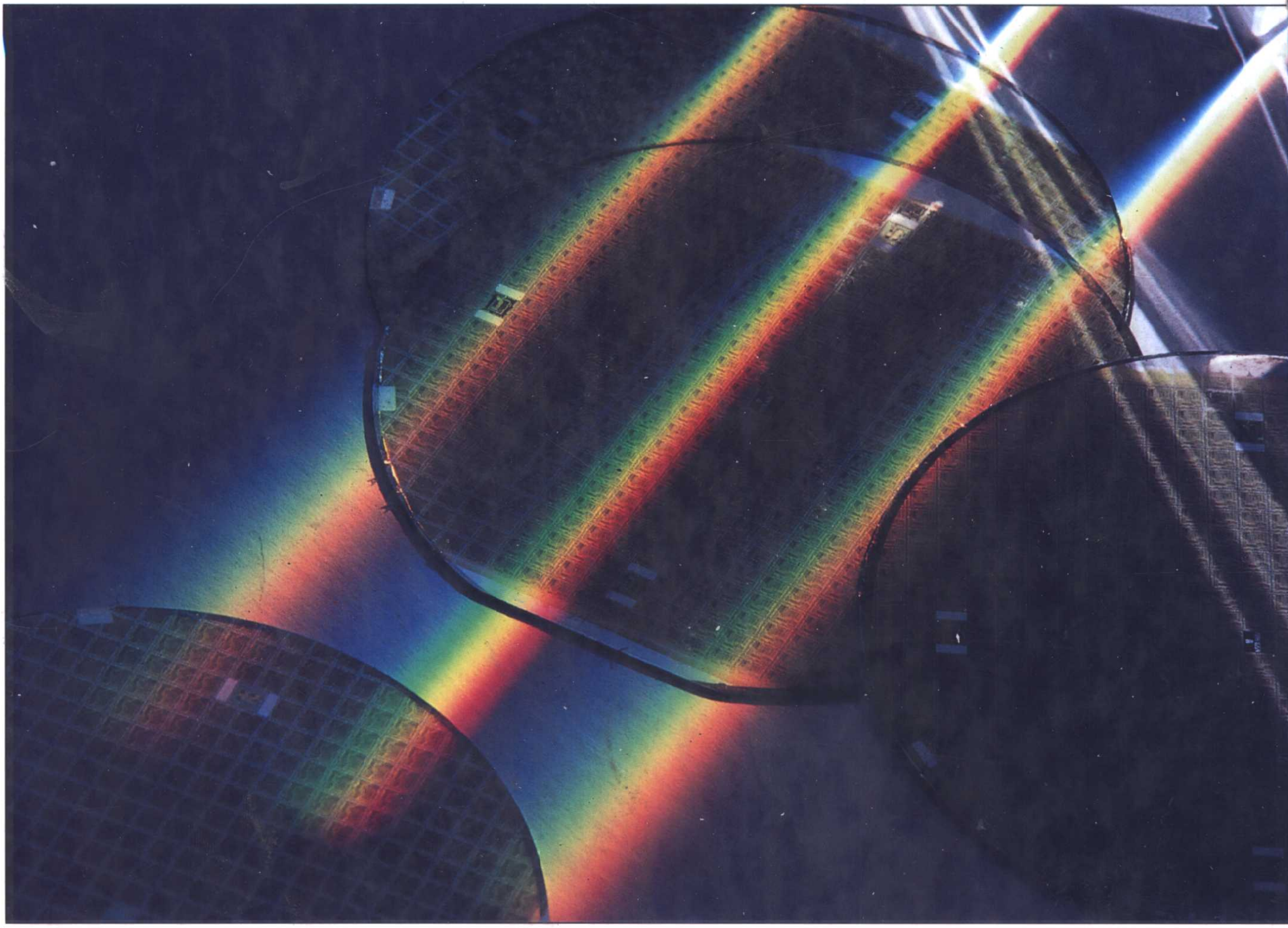

SEMICONDUCTOR PHYSICS & DEVICES

BASIC PRINCIPLES

SECOND EDITION

DONALD A. NEAMEN

SEMICONDUCTOR PHYSICS AND DEVICES

Basic Principles

SECOND EDITION

Donald A. Neamen
University of New Mexico

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ABOUT THE AUTHOR

Donald Neamen is a professor and associate chairman for the Department of Electrical and Computer Engineering at The University of New Mexico. He received his Ph.D. from The University of New Mexico and then became an electronics engineer at the Solid State Sciences Laboratory at Hanscom Air Force Base. In 1976, he became an Assistant Professor in the EECE department at The University of New Mexico, where he teaches the semiconductor physics and devices course and the electronics courses.

In 1980, Professor Neamen received the Outstanding Teacher Award for The University of New Mexico. In 1983 and 1985, he was recognized as Outstanding Teacher in the College of Engineering by Tau Beta Pi. In 1990, 1994, 1995, and 1996, he received the Faculty Recognition Award, presented by graduating EECE students. He was also honored with the Teaching Excellence Award in the College of Engineering for 1994.

In addition to his teaching, Professor Neamen has worked in industry with Martin Marietta, Sandia National Laboratories, and Raytheon Company. He has published many papers and is the author of *Electronic Circuit Analysis and Design.*

PREFACE

PHILOSOPHY AND GOALS

The purpose of the second edition of this book is to provide a basis for understanding the characteristics, operation, and limitations of semiconductor devices. In order to gain this understanding, it is essential to have a thorough knowledge of the physics of the semiconductor material. The goal of this book is to bring together quantum mechanics, the quantum theory of solids, semiconductor material physics, and semiconductor device physics. All of these components are vital to the understanding of both the operation of present day devices and any future development in the field.

The amount of physics presented in this text is greater than what is covered in many introductory semiconductor device books. Although this coverage is more extensive, the author has found that once the basic introductory and material physics have been thoroughly covered, the physics of the semiconductor device follows quite naturally and can be covered fairly quickly and efficiently. The emphasis on the underlying physics will also be a benefit in understanding and perhaps in developing new semiconductor devices.

Since the objective of this text is to provide an introduction to the theory of semiconductor devices, there is a great deal of advanced theory that is not considered. In addition, fabrication processes are not described in detail. There are a few references and general discussions about processing techniques such as diffusion and ion implantation, but only where the results of this processing have direct impact on device characteristics.

PREREQUISITES

This book is intended for junior and senior undergraduates. The prerequisites for understanding the material are college mathematics, up to and including differential equations, and college physics, including an introduction to modern physics and electrostatics. Prior completion of an introductory course in electronic circuits is helpful, but not essential.

ORGANIZATION

The presentation in the second edition is slightly different compared to that in the first edition. The text begins with the introductory physics, moves on to the semiconductor material physics, and then covers the physics of semiconductor devices. Chapter 1 presents an introduction to the crystal structure of solids, leading to the ideal single-crystal semiconductor material. Chapter 2 introduces quantum mechanics and the quantum theory of solids, which together provide the necessary basic physics.

Chapters 3 through 5 cover the semiconductor material physics. Chapter 3 presents the physics of the semiconductor in thermal equilibrium; Chapter 4 treats the transport phenomena of the charge carriers in a semiconductor. The nonequilibrium excess carrier characteristics are then developed in Chapter 5. Understanding the behavior of excess carriers in a semiconductor is vital to the goal of understanding the device physics.

The physics of the basic semiconductor devices is developed in Chapters 6 through 12. Chapter 6 treats the electrostatics of the basic pn junction, and Chapter 7 covers the current-voltage characteristics of the pn junction, as well as a discussion of the solar cell. Metal-semiconductor junctions, both rectifying and nonrectifying, and semiconductor heterojunctions are considered in Chapter 8, while Chapter 9 treats the bipolar transistor. The physics of the metal-oxide-semiconductor field-effect transistor is presented in Chapters 10 and 11, and Chapter 12 covers the junction field-effect transistor. Once the physics of the pn junction is developed, the chapters dealing with the three basic transistors may be covered in any order—these chapters are written so as not to depend on one another.

NEW TO THE SECOND EDITION

New to the second edition are computer simulation problems, an emphasis on design, and an interactive, electronic workbook using Mathcad, in which selected problems from the text are recast in the Mathcad environment in order to permit greater flexibility for students and assist them in gaining a stronger conceptual understanding of the material discussed in the text.

- **Computer Simulations:** Computer simulations are included at the end of most chapters. The problems are not dependent on any particular simulation program, so readers are free to use the program with which they are most comfortable. Keep in mind that computer simulation is used as a tool to solve problems more conveniently, but it does not replace learning the fundamentals of semiconductor device physics.
- **Design Examples and Problems:** Design is at the heart of engineering. Design examples have been incorporated throughout the chapters to serve as a first step in developing an intuition that can be applied to the design process. Problems at the end of most chapters in a Summary and Review section are, for the most part, open-ended design problems.
- **Mathcad Electronic Workbook:** For those students seeking additional practice or desiring a deeper and broader understanding of the material discussed in the text, the new Mathcad electronic workbook should prove to be a valuable tool. Equipped with its own Mathcad engine, the Mathcad electronic workbook does

not require the additional purchase of the full-blown Mathcad software. The workbook includes two to three problems and their extensions taken from each chapter of the text, reconfigured electronically. The student is thus freed from performing tedious calculations and at the same time has the freedom to change the parameters of a given problem in order to explore a variety of outcomes.

Each of these new types of problems and examples is identified with its own icon in the text, as indicated below:

Computer Simulations

Design Problems and Examples

ADDITIONAL FEATURES

- A Preview section introduces each chapter, generally beginning with a discussion of how the material from the previous chapter will be used in the present chapter. The preview section then gives the topics to be covered in the chapter, elucidates the importance of these topics, and explains how they fit into the overall picture.
- An extensive number of examples, including design examples, are used throughout the text to reinforce the theoretical concepts being developed.
- A Summary and Review section follows the text of each chapter. This section summarizes the results that were derived in the chapter and reviews the basic concepts that were developed. The section ends by discussing the significance of the material to the remaining chapters.
- A Glossary of Important Terms follows the Summary and Review section of each chapter.
- A large number of problems are given at the end of each chapter, organized according to the subject of each section in the chapter body. These are design and open-ended problems. Computer simulation problems are also included at the end of most chapters.
- A Reading List finishes up each chapter. The references that are at an advanced level compared with the level of this text are indicated by an asterisk.
- Answers to selected problems are given in the last appendix. Knowing the answer to a problem is an aid and a reinforcement in problem solving.

SUPPLEMENTS

- A solutions manual is available for instructors.
- Transparency masters are also available.
- A Mathcad electronic workbook is provided for students.

USE OF THE BOOK

The text is intended for a one-semester course at the junior or senior level. As with most textbooks, there is more material than can be conveniently covered in one semester; this allows each instructor some flexibility in designing the course to his or her own specific needs. However, the text is not an encyclopedia. Sections in each chapter that can be skipped without loss of continuity are identified by an asterisk in both the table of contents and in the chapter itself. These sections, although important to the development of semiconductor device physics, can be postponed to a later time.

The material in the text has been used extensively in a course that is required for junior-level electrical engineering students at the University of New Mexico. Slightly less than half of the semester is devoted to the first five chapters; the remainder of the semester is devoted to the pn junction, the bipolar transistor, and the metal-oxide-semiconductor field-effect transistor. A few other special topics may be briefly considered near the end of the semester.

Although the bipolar transistor is discussed in Chapter 9 before the MOSFET or JFET, each chapter, dealing with one of the three basic types of transistors, is written to stand alone. Any one of the transistor types may be covered first.

NOTES TO THE READER

This book introduces the physics of semiconductor materials and devices. Although many electrical engineering students are more comfortable building electronic circuits or writing computer programs than studying the underlying principles of semiconductor devices, the material presented here is vital to an understanding of the limitations of electronic devices, such as the microprocessor.

Mathematics is used extensively throughout the book. This may at times seem tedious, but the end result is an understanding that will not otherwise occur. Although some of the mathematical models used to describe physical processes may seem abstract, they have withstood the test of time in their ability to describe and predict these physical processes.

The reader is encouraged to continually refer to the preview sections so that the objective of the chapter and the purposes of each topic can be kept in mind. This constant review is especially important in the first five chapters, dealing with basic physics.

The reader must keep in mind that, although some sections may be skipped without loss of continuity, many instructors will choose to cover these topics. The fact that sections are marked with an asterisk does not minimize the importance of these subjects.

It is also important that the reader keep in mind that there may be questions still unanswered at the end of a course. Although the author dislikes the phrase, "it can be shown that. . .," there are some concepts used here that rely on derivations beyond the scope of the text. This book is intended as an introduction to the subject. Those questions remaining unanswered at the end of the course, the reader is encouraged to keep "in a desk drawer." Then, during the next course in this area of concentration, he or she can take out these questions and search for the answers.

ACKNOWLEDGMENTS

I am indebted to the many students I have had over the years who have helped in the evolution of the first edition as well as the second edition of this text. I am grateful for their enthusiasm and constructive criticism. The University of New Mexico has my appreciation for providing an atmosphere conducive to writing this book.

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I appreciate the many fine and thorough reviews—your suggestions have made this a better book.

Donald A. Neamen

READING LIST

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D.A.N.

prologue

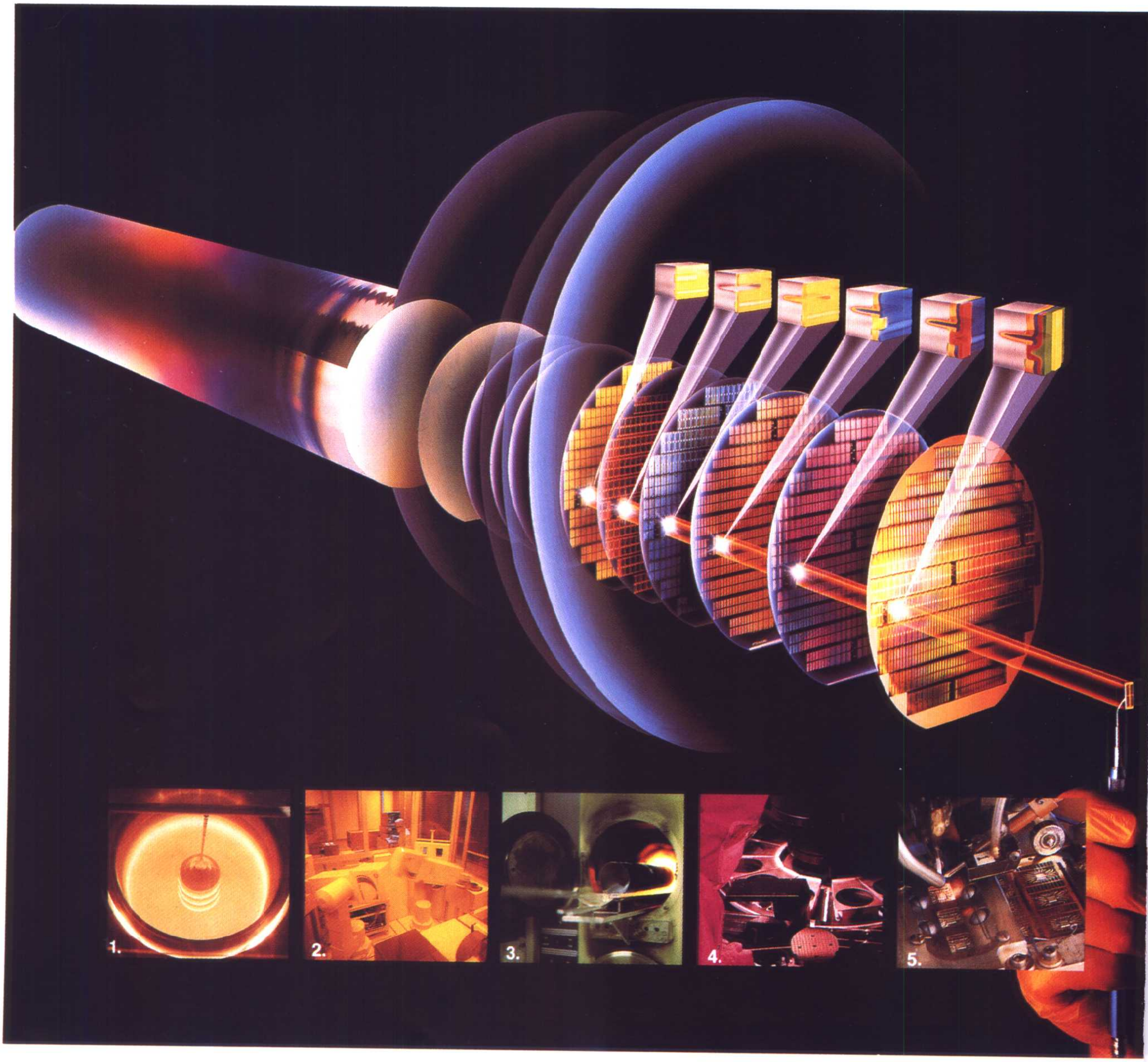
Semiconductors and the Integrated Circuit

The development of the transistor and the integrated circuit (IC) has led to remarkable electronic capabilities. The IC permeates almost every facet of our daily lives. Perhaps the most dramatic example of IC technology is the digital computer—a relatively small desktop computer today has more capability than the equipment that just a few years ago would fill a whole room. The semiconductor electronics field continues to be fast-changing one, with thousands of papers published each year.

The semiconductor device has a fairly long history, although the greatest explosion of IC technology has occured during the last two decades.[1] The metal-semiconductor contact dates back to the early work of Braun in 1874, who discovered the asymmetric nature of electrical conduction between metal contacts and semiconductors, such as copper, iron, and lead sulphide. These devices were used as detectors in early experiments on radio. In 1906, Pickard took out a patent for a point contact detector using silicon and, in 1907, Pierce published rectification characteristics of diodes made by sputtering metals onto a variety of semiconductors.

By 1935, selenium rectifiers and silicon point contact diodes were available for use as radio detectors. With the development of radar, the need for detector diodes and mixers increased. Methods of achieving high-purity silicon and germanium were developed during this time. A significant advance in our understanding of the metal-semiconductor contact was aided by developments in the semiconductor physics. Perhaps most important during this period was Bethe's thermionic-emission theory in 1942, according to which the current is determined by the process of emission of electrons into the metal rather than by drift or diffusion.

[1]This brief introduction is intended to give a flavor of the history of the semiconductor device and integrated circuit. Thousands of engineers and scientists have made significant contributions to the development of semiconductor electronics—the few events and names mentioned here are not meant to imply that these are the only significant events or people involved in the semiconductor history.



Compliments of Texas Instruments Incorporated

The Creation of an Integrated Circuit

Placing 1 million transistors in a space this size [ ] is one of the most complex manufacturing operations imaginable. Yet Texas Instruments daily manufactures millions of integrated circuit—chips—of astonishing complexity and intricacy.

The precision involved is measured in microns or smaller; a micron being one-millionth of a meter or about one-fiftieth the diameter of a human hair; fabrication facilities are 1,000 times cleaner than the cleanest operating rooms; and billions of dollars have been invested in robots and other highly automated machinery.

Shown here are five major steps in the process of building an integrated circuit, plus an overview of an advanced technique called "trenching." It was developed by TI for making high-density memory chips.

1. Crystal Growth and Slicing A chip begins with drawing a silicon ingot in a fiery furnace containing molten silicon. Special high-speed saws slice the ingots into wafers about the thickness of a dime, and they are then ground thinner and polished mirror smooth.

2. Photolithography Patterning Creating the actual circuity of each chip is done by photolithography. In this process, masks are used to expose a chemical coating called photoresist to ultraviolet light. This causes the photoresist to harden in desired patterns when developed.

3. Diffusion An early step in building a chip is baking (diffusing) impurities into the silicon wafers in a diffusion furnace. The impurities alter the electrical characteristics of the silicon, creating separate regions with excess negative or positive charges. To determine the flow of these charges in any circuit, the impurities are diffused along a pattern defined by previous photolithography and etching processes. The example shown is the beginning of a high-density memory chip.

4. Etching In this operation, the wafer moves to a plasma reactor where electrically excited gases etch the surface into the pattern defined by the photolithography process. In this manner, trenches—about three microns deep—are etched into the water. The trenches conserve valuable surface area and allow TI to place a million capacitors and a million transistors on a single chip.

Repeating this basic cycle—laying down materials, patterning, and etching—builds up the layers of the circuit. One of the final steps is to lay down an aluminum interconnect pattern that joins (integrates) the circuit components. In the case of the example, the connection to the aluminium interconnect pattern occurs at the edges of the chips.

5. Assembly, Bonding, and Packaging The finished chips (there can be hundreds on each wafer) are tested, separated from each other, mounted in a frame, and wired to fit product specifications. The mounted chips are then sealed in packages of either ceramic or plastic to prevent damage and contamination and to facilitate handling. A series of stress tests simulating operating environments and a final electrical test assure reliability.

Another big breakthrough came in December 1947 when the first transistor was constructed and tested at Bell Telephone Laboratories by William Shockley, John Bardeen, and Walter Brattain. This first transistor was a point contact device and used polycrystalline germanium. The transistor effect was soon demonstrated in silicon as well. A significant improvement occurred at the end of 1949 when single-crystal material was used rather than the polycrystalline material. The single crystal yields uniform and improved properties throughout the whole semiconductor material.

The next significant step in the development of the transistor was the use of the diffusion process to form the necessary junctions. This process allowed better control of the transistor characteristics and yielded higher-frequency devices. The diffused mesa transistor was commercially available in germanium in 1957 and in silicon in 1958. The diffusion process also allowed many transistors to be fabricated on a single silicon slice, so the cost of these devices decreased.

Up to this point, each component in an electronic circuit had to be individually connected by wires. In September 1958, Jack Kilby of Texas Instruments demonstrated the first integrated circuit, which was fabricated in germanium. At about the same time, Robert Noyce of Fairchild Semiconductor introduced the integrated circuit in silicon using a planar technology. These first circuit used bipolar transistors. Practical MOS transistors were then developed in the mid-60s. The MOS technologies, especially CMOS, have become a major focus for IC design and development. Silicon is the main semiconductor material. Gallium arsenide and other compound semiconductors are used for special applications requiring very high frequency devices and for optical devices.

Since that first IC, circuit design has become more sophisticated, and the integrated circuit more complex. A single silicon chip may be on the order of 1 square centimeter and contain over a million transistors. Some ICs may have more than a hundred terminals, while an individual transistor has only three. An IC can contain the arithmetic, logic, and memory functions on a single semiconductor chip—the primary example of this type of IC is the microprocessor. Intense research on silicon processing and increased automation in design and manufacturing have led to lower costs and higher fabrication yields.

Understanding the semiconductor device and its characteristics must start with the semiconductor material. A specific goal of this text is to introduce the basic physics of the semiconductor material. This basic knowledge will lead to a sound understanding of existing devices, and it is also fundamental for understanding or developing new devices. The physics of semiconductor materials and devices will be covered in this text. Although semiconductor processing is an extremely important part of the IC technology, it is a topic left for other texts.

CONTENTS IN BRIEF

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