Second Edition

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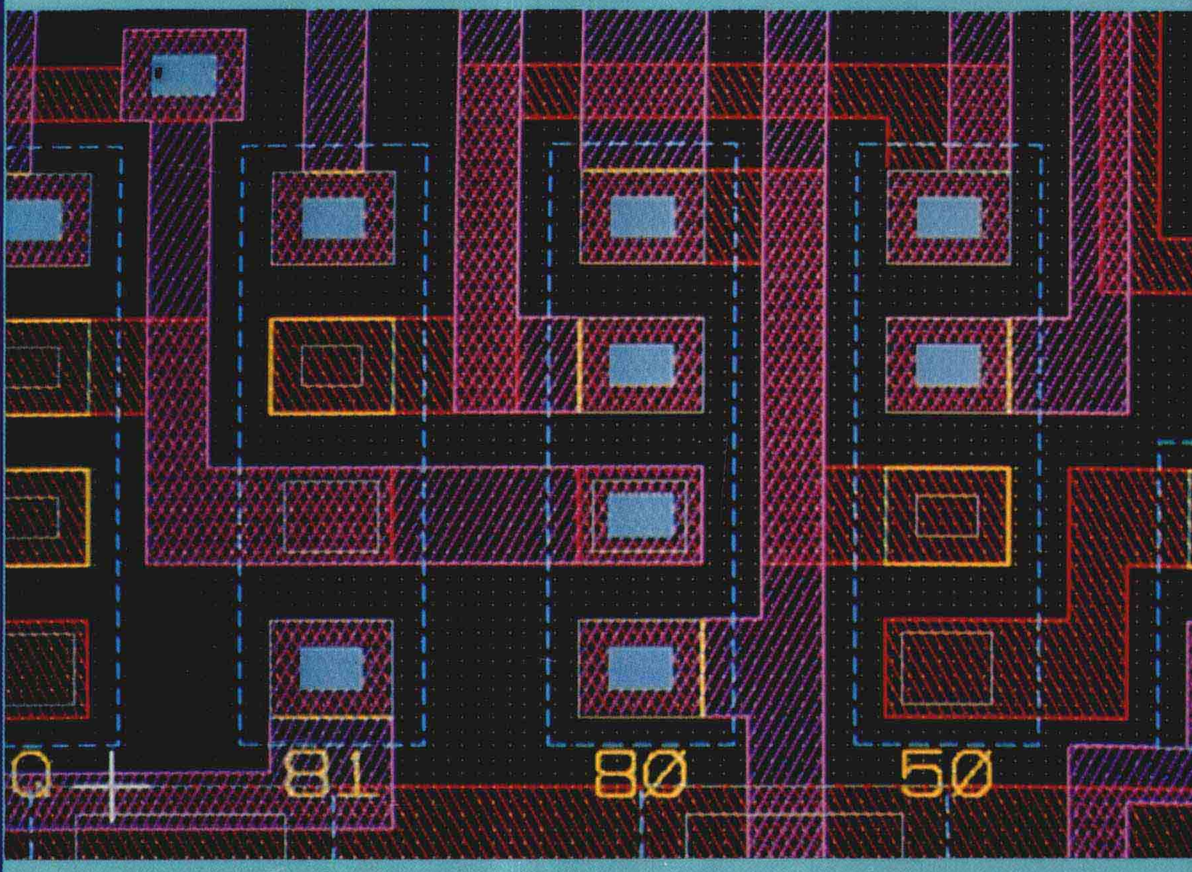
Jacob Millman
Arvin Grabel



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ABOUT THE AUTHORS

Jacob Millman is Professor Emeritus of Columbia University, where he held the Charles Batchelor Chair in Electronics. He obtained his B.S. (1932) and Ph.D. (1935) in physics from the Massachusetts Institute of Technology. His first graduate year was spent in Munich, Germany (1932–1933). He taught electrical engineering at the City College of New York (1936–1941 and 1946–1951) and at Columbia (1952–1975). During World War II he worked on the development of radar systems at the Radiation Laboratory of MIT (1942–1945).

Dr. Millman is the author or coauthor of eight textbooks; *Electronics* (1941 and revised in 1952); *Pulse and Digital Circuits* (1956); *Vacuum-Tube and Semiconductor Electronics* (1958); *Pulse, Digital, and Switching Waveforms* (1965); *Electronic Devices and Circuits* (1967); *Integrated Electronics* (1972); *Electronic Fundamentals and Applications* (1975); and *Microelectronics* (1979). These books have been translated into ten languages.

Professor Millman is a Fellow and Life Member of the IEEE and a Fellow of the American Physical Society. He was given the Great Teachers Award of Columbia University (1967), the Education Medal of the IEEE (1970), and was elected to the IEEE Centenial Hall of Fame as one of the All-Time Top Electrical Engineering Educators (1984).

He has lectured extensively outside the United States: Italy, Spain, Israel, Greece, Brazil, Uruguay, Germany, Holland, and France.

Arvin Grabel has served on the faculty at Northeastern University since 1964 and is currently Professor of Electrical and Computer Engineering. He obtained all three degrees from New York University. As Instructor of Electrical Engineering he taught at the New York University Graduate Center at Bell Laboratories. Professor Grabel has been Visiting Professor at the University of California at Santa Barbara and The Cooper Union for the Advancement of Art and Science. "Basic Electrical Engineering," of which he is a coauthor, is now in its fifth edition and has been translated into six languages.

PREFACE

The primary objective of this book—as it was for the previous edition—is to serve as the text in modern electronics courses for electrical engineering, computer engineering, and computer science students. Our approach is to stress the fundamental concepts that underlie the physical operation, analysis, and design of integrated circuits and systems. By coupling this appoach with a diversity of applications we hope to convey both the substance and flavor of the subject. The breadth and depth of treatment also makes this volume a valuable adjunct to the continuing education of practicing engineers, scientists, and professionals in fields akin to electrical and computer engineering.

This book is an extensive rewritten version of the first edition, and a substantial amount of new material has been added to reflect changes in technology and curricula. The text, divided into five major sections, is organized to provide maximum pedagogical flexibility without loss of continuity. Thus, the individual faculty member can adapt the material to a number of different courses which suit the needs and interests of both students and professors.

Part 1 (Chapters 1 to 5) focuses on the behavior of the major *semiconductor devices* used in integrated circuits (ICs). The five chapters outline the properties of semiconductors and explain the physical operation and circuit characteristics of junction diodes, bipolar transistors (BJTs), and field-effect transistors (FETs). The last chapter describes IC fabrication techniques. Its intent is to provide the student with an overview of the processes employed and the constraints imposed by fabrication on circuit design.

These first five chapters are intended for students who have had no previous course in electronics. They supply the fundamental material required for an understanding of the rest of the book. The mathematics and physics background obtained in the first year or two of a typical engineering program is the only prerequisite for Part 1. Most students also have had a course in circuit analysis prior to studying electronics. While this preparation is valuable, it is not essential because the elementary circuit analysis used in these chapters is explained in Appendix C.

Part 2 (Chapters 6 to 9) treats *digital circuits and systems*, and Part 3 (Chapters 10-14) deals with *amplifier circuits and systems*. Part 3 (analog) may be taken up before Part 2 (digital) if desired. The material contained in Part 1 provides the necessary background for either section. Our reasons for introducing digital material first are twofold:

1. In many universities, computer engineering and science majors are required to take only one electronics course. Clearly, for these students such a course should concentrate on digital electronics. Judicious selection of topics in Parts 1 and 2 can create a satisfactory one-term course, and this opportunity gives the instructor the freedom and the incentive to consider the subject matter most appropriate to his or her objectives.
2. Only elementary circuit theory of the level described in Appendix C is required. Consequently, the student need not have any electrical engineering prerequisites to handle these topics.

The first chapter in Part 2 treats the basic logic-gate building blocks used in digital systems. We concentrate on the operation and performance of the four major IC technologies. The two field-effect transistor (FET) families are NMOS and CMOS, whereas transistor-transistor logic (TTL) and emitter-coupled logic (ECL) are the standard bipolar junction transistor (BJT) logic families investigated. The standard small-scale integration (SSI), medium-scale integration (MSI), and large-scale integration (LSI) circuits and systems derived from these logic gates are developed in the next two chapters (combinatorial and sequential circuits and systems). The last chapter deals with very large scale integration (VLSI) systems in which static and dynamic random-access memory (RAM) cells are discussed. Technologies used only in VLSI systems, such as integrated-injection logic (I^2L), CMOS domino logic, and charge-coupled devices (CCD), are also introduced.

The development in Part 3 (Chapters 10 to 14) on *amplifier circuits and systems* parallels that in Part 2. The initial pair of chapters focuses on the properties of basic BJT and FET amplifier stages. Methods by which IC transistors are biased are presented; the use of small-signal models to evaluate the preformance of single-stage and cascaded amplifiers is discussed. The operational amplifier (Op-Amp) as a basic building block is also described. These amplifiers are used to form feedback-amplifier systems. The fundamental feedback concepts and techniques developed are used in the analysis and design of the four basic feedback-amplifier topologies. The internal architecture and performance of modern Op-Amp chips are examined in Chapter 14 and serve to bring together many of the concepts previously encountered in Part 3.

Part 4 (Chapters 15 and 16) examines the circuit and systems aspect of *data acquisition and signal processing*. Many of these circuits are used in both digital and analog systems and employ both logic gates and Op-Amps. Circuits for the generation of sinusoidal, ramp, and pulse waveforms and the conversion of analog signals to digital signals (or vice versa) are discussed. Integrators, active filters including switched-capacitor filters, multipliers, and logarithmic amplifiers are among the signal-conditioning circuits described.

The last part (Chapter 17) exposes the student to electronic *power circuits* *and systems*. The conversion of ac to dc is treated and leads to a discussion of monolithic voltage regulators. High-voltage and high-power amplifier devices and circuits are also examined.

This text contains enough material for 2 or 3 one-semester electronics devices-circuits-systems courses. With the ever-increasing component density on an IC chip, the difference between an electronic device, circuit, and system has become quite blurred, and in this book no attempt is made to distinguish between them. An entire monolithic package, such as an Op-Amp, is often referred to as a *device*. Of course, a single transistor is clearly a *device* and a large-scale microelectronic chip merits the designation *system* or at least *subsystem*.

A brief historical survey of electronics is in the Prologue (following this preface). It is hoped that both the instructor and student will read this fascinating history before beginning the study of the text.

Most electronic engineers design a new product, subsystem, or system by interconnecting standard IC chips so that the overall assembly achieves the desired external objectives. Clearly these engineers must know what IC chips are commercially available, what function they perform, and what their limitations are. Chip designers must be aware of what functions need to be performed and what limitations most affect the performance of the systems in which the chips are used.

From this perspective, the goal of this book is to take the reader step by step from a qualitative knowledge of semiconductor properties to an understanding of the operation of solid-state devices and finally to an appreciation for how these are combined to form ICs with distinct and useful input-output characteristics. A very broad variety of IC chips are studied in this book. We describe not only what is fabricated, but also attempt to convey a deep understanding of the digital and/or analog functions performed by the chip. After each circuit or system is studied, reference is made to a specific commercially available chip which realizes the desired function. Practical limitations of real rather than ideal devices and circuits are explained. To appreciate nonideal behavior, manufacturer's specifications of representative devices and integrated circuits are given in Appendix B. The depth of discussion, the broad choice of topics, and the practical emphasis combine to prepare the student to do useful engineering immediately upon graduation.

The attention given to pedagogy is reflected in the explanation of device-circuit-system behavior and in the context in which the specific topics are discussed. We have been diligent in our efforts to ensure that new concepts are introduced by the use of familiar analytic techniques and that the development of new methods of analysis relies only on concepts previously encountered. Also, considerable care was exercised in the selection of the many illustrative examples and numerical calculations incorporated in the body of the text.

Many of the methods of analysis discussed lead to the "pencil-and-paper" calculations which an engineer often performs. Such computations are invaluable as they help develop insight into the behavior of the circuit or system being designed. When used in conjunction with computer simulations, they provide the engineer with powerful design tools. Students should be encouraged to use circuit simulations such as SPICE and MICROCAP II, both of which are available for use with personal computers.

The review questions at the end of each chapter are a significant adjunct to the approximately 800 problems given in Appendix D. Many of these problems are new, and the majority of the problems used in the earlier edition have been modified. Used together, the questions and problems test the students' grasp of fundamental concepts and provide experience in the design and analysis of electronic circuits. Realistic parameter values are used in virtually all numerical problems.

The review questions test the students' qualitative knowledge of the text material. These can also be used very effectively as part of a quiz or an exam.

A solutions manual is available to an instructor who has adopted the text. As an added pedagogical aid, transparencies of over 100 involved figures in the book are also available to the instructor.

We have had the benefit of valuable advice and suggestions from the many professors and engineers working in industry who used the first edition as either instructor, student, or practicing engineer. All these individuals have influenced this edition and to them, we express our thanks and appreciation. We are especially grateful to Professor Arthur Dickerson whose comments and insight were invaluable in the preparation of this book.

We are indebted to David Damstra, who from manuscript through production contributed much to this book; to the comments of and reviews provided by Sanjeev Rao; and to Mary Rosenberg, whose proofing of final pages was a great help.

Jacob Millman
Arvin Grabel

P.S. I am among the two generations of electrical engineers who have studied electronics from Jacob Millman's books. I had the pleasure of once again being Professor Millman's "student" when we worked closely together in the planning and organization of this book and in the detailed preparation of the first six chapters. I have attempted to convey the guiding spirit of this truly remarkable teacher and writer in the remainder of this text. The last eleven chapters were my sole responsibility and therefore a reflection of the quality of the student and not the mentor.

I am indebted to Jacob Millman for the opportunity of collaborating with him. His influence and style have contributed immeasurably to me as teacher and author.

Arvin Grabel

CONTENTS

Prologue
A BRIEF HISTORY OF ELECTRONICS

Electronics—to most of us this brings to mind a variety of things from "chips" and computers to television and transistors. Yet, while we agree on specific items that constitute electronics, its definition is elusive. In the next several paragraphs and the remainder of this prologue, we define electronics as used in this book not in the dictionary sense, but in a manner which attempts to convey the flavor and nuance of the discipline. We have chosen history as the vehicle to accomplish this because it is the efforts of individuals who contribute and have contributed to the field that truly define the discipline.

Electronics, in the strictest sense, is the science and technology of the motion of charges in a gas, vacuum, or semiconductor. Note that charge motion confined to a metal is not considered electronics. This was an historical division used early in the twentieth century to separate the already flourishing field of electrical engineering from the new and emerging field of electronic engineering. At that time electrical engineering dealt with devices that depended solely on the motion of electrons in metals, such as motors, generators, light bulbs, and wire communication systems (telephone and telegraph). As we approach the end of the twentieth century, however, the historical division between electrical and electronic engineering no longer serves its original function.

Today practicing electrical engineers perform diverse functions (design, development, production, research, and even teaching) with varied applications. They deal with systems by which we can communicate with one another worldwide, by which vast quantities of data are manipulated, and by which highly complex manufacturing processes are automated and with the elements used to realize them. The province of electrical engineering also includes the devices, circuits, and systems used for the generation, distribution, and conversion of electric energy. The group mentioned in the first of the two previous sentences possesses the common property of processing information; the group mentioned in the second can be regarded as processing energy. This distinction between information processing and energy processing serves to separate electronics