Rudolf F. Graf

Encyclopedia of ELECTRONIC CIRCUITS

Volume 3

Analysis and Design of Integrated Electronic Circuits

SECOND EDITION

PAUL M. CHIRLIAN

Stevens Institute of Technology

HARPER & ROW, PUBLISHERS, New York
Cambridge, Philadelphia, San Francisco, Washington,
London, Mexico City, São Paulo, Singapore, Sydney

1817

Sponsoring Editor: Peter Richardson
Project Editor: Ellen MacElree
Cover Design: Robin Hessel/Brand X Studios
Text Art: Fineline Illustrations, Inc.
Production: Brenda DeMartini
Compositor: Composition House Limited
Printer and Binder: The Maple Press Company

Analysis and Design of Integrated Electronic Circuits, Second Edition

Library of Congress Cataloging in Publication Data

Chirlian, Paul M.
Analysis and design of integrated electronic circuits.

Includes bibliographies and index.
1. Integrated circuits. I. Title.
TK7874.C544 1987 621.381'73 86-18334
ISBN 0-06-041253-4

86 87 88 89 9 8 7 6 5 4 3 2 1

Preface

This is the second edition of an undergraduate textbook that covers the core topics in electronics that all electrical engineers should know. The book has been upgraded to reflect changes in technology and in electrical engineering curricula. This text concentrates mainly on electronic circuits, so that changes in circuitry, rather than in device structure, are stressed. The philosophy remains the same: It is important that the electrical engineer have a thorough understanding of the analytic tools needed to analyze and design electronic circuits. Therefore, topics such as modeling still are discussed in detail. The electrical engineer must be better educated than the technician, and so the mathematical viewpoint of the first edition has been carried over into the second edition.

The following are some of the principal changes in the second edition.

A discussion of high-speed TTL has been included in Chapter 9, and the discussion of STTL has been extended.

A thorough discussion of the use of mixed-logic representation has been integrated at appropriate points throughout the book. In addition, dependency notation is discussed in detail.

The effects of poor feedback design are covered in Chapter 16. In particular, the relation between poor design and the so-called "transient intermodulation distortion" is considered.

Switched-capacitor filters are discussed. There is sufficient detail included here so that the reader will know how to design simple switched-capacitor filters. Circuits that minimize the effects of stray capacitance are considered. The z transform is not used in this discussion because z transforms are not presumed to be a prerequisite for a course in which this book is used. However, the need for the use of z transforms by the serious worker in the switched-capacitor field is discussed. The periodic frequency response of switched-capacitor filters is presented, and the use of analog prefilters is considered.

The chapter on microprocessors has been removed. Most electrical engineering curricula now include courses on microprocessors so that it is not necessary to include this material in the electronic-circuits courses. Because the material is now typically covered in communication courses, the chapter on modulation and demodulation has also been removed.

The notation used in the figures has been changed. The polarity of the voltages is no longer designated by an arrow. Instead, only plus and minus signs are used.

Finally, the second edition has been checked very carefully for errors. After considerable class testing and detailed study, a number of errors have been located and removed from this second edition. We have made every effort to make the text error-free.

Analysis and Design of Integrated Electronic Circuits continues to provide students at the junior and senior levels with a thorough understanding of most electronic circuits and the procedures used to analyze and design them. Integrated circuits and their applications are stressed. However, the use of discrete devices such as junction transistors and FETs is also considered. Many numerical examples of both analysis and design are incorporated throughout the book. It is hoped that, from these, the student will develop a general design philosophy that can be used with all electronic circuit designs.

This is an electronic circuits text and, therefore, there will be no detailed discussion of semiconductor physics. However, the first four chapters of the book do present enough information in order that a basic understanding of semiconductor electronic devices can be obtained.

In Chapters 1 through 3, the physics and basic principles of semiconductors, *p-n* junction diodes, and transistors arc discussed. The discussion of physics is brief. If is sufficiently detailed, however, so that the reader will understand the basics. Such things as junction capacitance, switching speed, characteristics, and ratings are discussed in detail.

The fabrication of integrated circuits is discussed in Chapter 4. The problems encountered are considered, and all types of fabrications are discussed. In Chapter 5 the graphical analysis techniques are presented. Because of the wide use of direct coupled circuits, their graphical analysis is considered in detail.

Modeling is discussed in Chapters 6 and 7. Chapter 6 concerns itself with linear models. Since the hybrid-pi model for the transistor is used throughout the book, this model is stressed. However, the *h*-parameter model is also thoroughly developed and related to the hybrid-pi model. The linear high-frequency model for the FET is also developed, and some basic amplifier circuits are also studied here. Pulse and large-signal models are the topics of Chapter 7. The Ebers and Moll model for the transistor and low-speed models for the FET are developed. Next, high-speed models are obtained. The usc of approximate models is discussed.

Chapters 8 through 11 are concerned with the basic ideas and circuits of digital systems. In Chapter 8, fundamental ideas such as number systems and gates are considered, and switching functions and Karnaugh maps are studied. All the commonly used logic families are discussed in Chapter 9. The electrical analysis of the various families is discussed there in great detail. Sequential circuits are the topic of Chapter 10. The design of both synchronous and asynchronous circuits is discussed in considerable detail. Various devices such as registers and counters are considered from both a design and an applications viewpoint. Memories are presented in Chapter 11. All of the semiconductor memories are thoroughly considered. There is also a discussion of CCD and magnetic bubble memories.

Broadband amplifiers are discussed in Chapter 12. This chapter starts with a general discussion of amplification. Next, single-stage amplifiers are studied, and finally, the design of multistage amplifiers is discussed. Transient and steady state response are considered. The chapter concludes with a discussion of noise. Operational amplifier applications are presented in great detail in Chapter 13. Many analog and digital circuits are discussed here to provide the reader with a thorough understanding of how operational amplifier circuits perform and how such circuits can be designed.

The actual circuitry within the operational amplifier chip is discussed in Chapter 14. Techniques for analyzing these circuits are presented. Small-signal and bias analyses are presented in a thorough analysis of the operational amplifier. Power amplifiers are discussed in Chapter 15. Transformerless push-pull amplifiers are stressed here and graphical analysis and design techniques are developed.

Feedback amplifiers are thoroughly discussed in Chapter 16. A rigorous, accurate discussion is given here. Although the mathematics level is kept suitable for a junior or senior level course, sufficient material is included, so the student understands what he or she is doing. The design of feedback systems using the Nyquist criterion and frequency compensation is discussed in great detail. Bandpass amplifiers are the topic of Chapter 17. Active filters and conventional tuned amplifiers are studied, Butterworth and Chebyshev frequency responses are developed, and the superheterodyne receiver is discussed.

Both sinusoidal and nonsinusoidal oscillators are studied in Chapter 18. Topics such as linear and nonlinear operation and frequency stabilization are also presented. Power supplies are considered in Chapter 19. Rectifiers, filters, and voltage regulators are studied. The design of switching regulators is considered in detail.

There are numerical examples amply distributed throughout the book. In addition, a large selection of homework problems is included at the end of each chapter. The instructor need not follow the order of these chapters exactly. For instance, the entire unit of Chapters 8 through 11 could be discussed toward the end of the book.

I would like to express my thanks to my colleagues Professors Alfred C. Gilmore, Jr., Stanley Smith, Edward Peskin, and Yusuf Z. Efe for the many helpful discussions during the writing of the first edition of this book, and also to the reviewers Professors J. D. Bargainer, A. J. Broderson, R. E. Lee, and J. H. Mulligan, Jr., for their many helpful comments on it.

I wish to express my gratitude to Professor Gilmore for his contributions to the second edition as well as the first and to the reviewers of the manuscript of the second edition, who read it with extreme care and made many helpful comments: David Greve, Carnegie Mellon University; Charles Nelson, CSU/Sacramento; Bruce Johnson, University of Nevada/Reno; David Soldan, Oklahoma State University; C. A. Ramblings, Southern Illinois University; Sidney Soclof, CSU/Los Angeles; David Green, University of Alabama/Birmingham; Russell Krackhardt, Worcester Polytechnic Institute; James Bargainer, Baylor University; and Giles Willis, Baylor University. I again express my loving and heartfelt thanks to my wife Barbara for her editing of the text and her encouragement.

PAUL M. CHIRLIAN

Contents

Preface xvii

Chapter 1 Semiconductors and the *p-n* Junction Diode 1

1-1. Semiconductors 2
1-2. Impure Semiconductors 5
1-3. Conduction Processes in Semiconductors 7
1-4. The *p-n* Junction 9
1-5. The Metal-Semiconductor Junction 15
1-6. The Practical *p-n* Junction Diode 15
1-7. *p-n* Junction Diode Ratings 21
1-8. Space-Charge, Transition, or Barrier Capacitance—Depletion Layer Width 22
1-9. Diffusion Capacitance—Charge Control 27
1-10. Switching the *p-n* Junction Diode—High-Frequency Effects 30
1-11. Light-Emitting Diodes—LED's 32
Problems 32
Bibliography 35

Chapter 2 The Junction Transistor 36

2-1. The Bipolar Junction Transistor 36
2-2. Current-Voltage Relations in the Junction Transistor 40
2-3. Common-Base Characteristics 41
2-4. Common-Emitter Characteristics—Active Region—Amplification 43
2-5. Common-Emitter Characteristics—Saturation and Cutoff Regions 49

2-6. Transfer Characteristics of the Common-Emitter Transistor Configuration 54
2-7. Common-Collector Configuration 56
2-8. Switching Speed and High-Frequency Effects in the Junction Transistor 56
2-9. Ratings of Junction Transistors 60
Problems 62
Bibliography 63

Chapter 3 The Field Effect Transistor 64

3-1. The Junction Field Effect Transistor 64
3-2. Metal-Oxide-Semiconductor FET—MOSFET; The Insulated-Gate FET—IGFET 68
3-3. The FET Amplifier—Dynamic Parameters 73
3-4. Saturation and Cutoff Operation of the FET 78
3-5. Switching Speed and High-Frequency Response of the FET 80
3-6. Ratings of FET's 81
Problems 83
Bibliography 85

Chapter 4 Integrated Circuit Fabrication 86

4-1. Planar Fabrication Processes for Transistors and Integrated Circuits 86
4-2. Monolithic Transistors—Isolation Techniques 91
4-3. Monolithic *p-n* Junction Diodes—Schottky Diodes 95
4-4. Monolithic MOSFET's 96
4-5. Monolithic Resistors and Capacitors 97
Problems 100
Bibliography 100

Chapter 5 Graphical Analysis 101

5-1. Rules for Notation 101
5-2. Biasing Procedures for the FET 102
5-3. Stabilization of the FET's Operating Point 107
5-4. A Direct Coupled FET Amplifier 111
5-5. FET Inverters—Active Loads—Complementary Symmetry 115
5-6. Basic Transistor Bias Circuits 121
5-7. Stability of the Junction Transistor's Operating Point 128
5-8. Operating Point Stabilization Circuits 132
5-9. A Direct Coupled Transistor Amplifier 136
5-10. The Direct Coupled Cascode Amplifier 141
5-11. Generalized Notation 144

5-12. Frequency Dependent Loads 145
5-13. Nonlinear Distortion 150
Problems 156
Bibliography 164

Chapter 6 Linear Models for Electronic Devices 165

6-1. The Low-Frequency Model of the FET—The Common-Source Amplifier 166
6-2. The Common-Drain FET Amplifier—The Source Follower 171
6-3. The Common-Gate FET Amplifier 175
6-4. Low-Frequency Junction Transistor Linear Models—Physical Discussion 176
6-5. Low-Frequency h-Parameter Models for the Junction Transistor 177
6-6. Analysis of Basic Transistor Amplifier Circuits Using h Parameters 186
6-7. High-Frequency Linear Models for the FET 196
6-8. Common-Source FET Amplifier—High-Frequency Input Admittance—Miller Effect 198
6-9. The Source Follower—High-Frequency Input Admittance 201
6-10. High-Frequency Linear Models for the Junction Transistor 204
6-11. Determination of Hybrid-pi Parameters from Published Data 208
6-12. Common-Emitter Amplifier—Input Admittance 211
Problems 214
Bibliography 222

Chapter 7 Pulse and Large-Signal Models for Electronic Devices 223

7-1. The Ebers-Moll Low-Speed Model for the Junction Transistor 223
7-2. Approximate Low-Speed Models for the Junction Transistor 226
7-3. Low-Speed Model for the FET 231
7-4. Approximate Low-Speed Models for the FET 232
7-5. High-Speed Model for the Bipolar Junction Transistor 236
7-6. Linear and Piecewise Linear Approximate High-Speed Models for the Junction Transistor 239
7-7. High-Speed Model for the FET 241
Problems 242
Bibliography 245

Chapter 8 Fundamental Elements of Digital Systems 246

8-1. Some Basic Ideas of Digital Circuits 246
8-2. Logical Operations 252

8-3. The AND Operation 253
8-4. The OR Operation 254
8-5. The Complement, or NOT, Operation 256
8-6. The NOR Operation 257
8-7. The NAND Operation 258
8-8. The Exclusive OR—XOR Operation 258
8-9. Functionally Complete Sets 260
8-10. Some Useful Relations—DeMorgan's Theorem 263
8-11. A Mixed-Logic Representation for Gate Circuits 266
8-12. Dependency Notation 270
8-13. Some Examples of Gate Circuits 276
8-14. A General Procedure for Expressing Arbitrary Switching Functions—Canonical Forms 279
8-15. Minimization of Switching Functions—Karnaugh Maps 288
8-16. Don't Care Conditions 294
Problems 295
Bibliography 299

Chapter 9 Logic Families 300

9-1. Characteristics of Logic Families 300
9-2. Diode Transistor Logic—DTL 302
9-3. An Improved DTL Circuit 310
9-4. High-Threshold Logic—HTL 312
9-5. Transistor-Transistor Logic—TTL 313
9-6. Wired Logic 319
9-7. Active Pull-up 322
9-8. High-Speed TTL 329
9-9. Resistor-Transistor Logic—RTL 331
9-10. Direct Coupled Transistor Logic—DCTL 335
9-11. Integrated-Injection Logic—I^2L 335
9-12. Schottky-Diode Nonsaturating Logic Circuits 340
9-13. Emitter-Coupled Logic—ECL—Nonsaturating Logic 342
9-14. MOSFET Logic 350
9-15. Complementary Symmetry MOSFET Logic—COSMOS Logic—CMOS Logic 354
9-16. Comparison of Logic Gates 356
9-17. Switching Time Specifications of Logic Gates 358
9-18. Manufacturers' Data 360
Problems 367
Bibliography 371

Chapter 10 Sequential Circuits and Their Design 372

10-1. Flip-Flops—Latches 373
10-2. The *R-S* Flip-Flop 374
10-3. The *J-K* Flip-Flop 382
10-4. The *T* Flip-Flop 384
10-5. The *D* Flip-Flop 385
10-6. Synchronizing and Triggering of Flip-Flops 386
10-7. Master-Slave Flip-Flops 389
10-8. The ac-Coupled Edge-Triggered Flip-Flop 393
10-9. The Capacitive-Storage Edge-Triggered Flip-Flop 397
10-10. Propagation-Delay Edge-Triggered Flip-Flops 398
10-11. Timing of Master-Slave and Edge-Triggered Flip-Flops 400
10-12. Registers 402
10-13. The Shift Register 403
10-14. More Complex Registers—Serial to Parallel and Parallel to Serial Conversion 406
10-15. Analysis Techniques for Synchronous Sequential Circuits 410
10-16. Design of Synchronous Sequential Circuits 416
10-17. Counters 424
10-18. Other Counter Circuits 431
10-19. Sequence Detectors and Generators 439
10-20. Asynchronous Sequential Circuits—Cycles—Races—Oscillation—Hazards 444
10-21. Design of Asynchronous Sequential Circuits 450
10-22. A Further Discussion of Dependency Notation 455
10-23. Integrated Circuit Implementation of Sequential Circuits 458
Problems 463
Bibliography 468

Chapter 11 Memories 469

11-1. Random Access Memories—RAM's 470
11-2. Bipolar Transistor RAM's 474
11-3. Schottky Transistor Memory Cells 480
11-4. I^2L Memory Cells 482
11-5. Static MOS RAM's 484
11-6. Dynamic MOS RAM's 486
11-7. Paralleling of RAM Memory Chips 490
11-8. Sequential Memories 494
11-9. MOS Sequential Memories 496
11-10. The Charge Coupled Device—CCD; CCD Sequential Memories 502
11-11. Read Only Memories—ROM's 508

11-12. The Programmable Logic Array—PLA 512
11-13. Magnetic Memories 514
11-14. The Magnetic Bubble Memory 516
11-15. Manufacturers' Data 523
Problems 523
Bibliography 525

Chapter 12 Small-Signal Untuned Amplifiers—Broadband Amplifiers 526

12-1. Frequency Distortion 526
12-2. Decibel Notation 530
12-3. Frequency Response of One Stage in a FET Common-Source Amplifier Cascade 535
12-4. Factors Affecting the Frequency Response of the One-Stage Common-Source FET Amplifier 547
12-5. Frequency Response of One Stage in a Junction Transistor Common-Emitter Amplifier Cascade 550
12-6. Factors Affecting the Frequency Response of the One-Stage Common-Emitter Transistor Amplifier 562
12-7. Bypass Capacitors 564
12-8. Source-Follower Amplifier 570
12-9. Emitter-Follower Amplifier 574
12-10. Common-Base Amplifier 580
12-11. Input and Output in a Cascade of Amplifiers 585
12-12. Bandwidth of Cascaded Amplifier Stages 587
12-13. Design of Broadband FET Amplifiers 589
12-14. Design of Broadband Transistor Amplifiers 597
12-15. The Cascode Amplifier Pair 609
12-16. Poles and Zeros 612
12-17. Transient Response 617
12-18. Noise—Amplifier Sensitivity 625
Problems 628
Bibliography 634

Chapter 13 Operational Amplifier Applications 635

13-1. The Ideal Operational Amplifier—The Quasi-ideal Operational Amplifier 635
13-2. The Simple Inverting Amplifier 638
13-3. Noninverting Amplifier Configurations 643
13-4. The Difference Amplifier—The Balanced Amplifier 644
13-5. Output Impedance 647

13-6. The Summer or Adder Circuit 649
13-7. The Integrator 652
13-8. A Simple Analog Computer 656
13-9. The Differentiator 657
13-10. The Logarithmic Amplifier 658
13-11. The Comparator 660
13-12. The Schmitt Trigger-Regenerative Comparator 664
13-13. Sample and Hold Circuits 667
13-14. Digital to Analog Converters 669
13-15. Analog to Digital Converters 673
Problems 681
Bibliography 684

Chapter 14 Operational Amplifier Circuitry—The Practical Operational Amplifier 685

14-1. The FET Differential Input Stage 685
14-2. The Junction Transistor—Differential Input Stage 689
14-3. The Cascode Differential Amplifier 693
14-4. High-Input Impedance Stages 694
14-5. Current Sources 700
14-6. Use of Current Sources as Load Impedances 708
14-7. Cascaded Differential Amplifiers—dc Stability 714
14-8. Output Stages 716
14-9. Bias Analysis of a Complete Operational Amplifier 723
14-10. The Signal Analysis of a Complete Operational Amplifier 731
14-11. The Darlington Transistor—Compound Transistors 733
14-12. The Frequency Response of Operational Amplifiers 734
14-13. Slewing Rate 739
14-14. Common Mode Problems 742
14-15. Offset Problems 744
14-16. Latch Up 746
14-17. Operational Amplifier Specifications 747
Problems 754
Bibliography 758

Chapter 15 Untuned Power Amplifiers 759

15-1. The Efficiency of Ideal Amplifiers 759
15-2. The Single Ended Amplifier 764
15-3. The Loudspeaker as a Load Impedance 771
15-4. The Complementary Symmetry Push-Pull Amplifier—Graphical Analysis 772

15-5. The Quasicomplementary Symmetry Push-Pull Amplifier 781
15-6. Distortion in Push-Pull Amplifiers 788
15-7. Design of Push-Pull Amplifiers 790
15-8. Push-Pull Amplifier with an Output Transformer 794
15-9. Thermal Design—Thermal Stability 797
Problems 803
Bibliography 808

Chapter 16 Feedback Amplifiers 809

16-1. Some Basic Ideas of Feedback Amplifiers 809
16-2. Two Very Simple Feedback Amplifiers 812
16-3. The Effect of Feedback on Sensitivity—The Importance of Return Difference and Loop Gain 815
16-4. The Effect of Feedback on Nonlinear Distortion 817
16-5. The Effect of Feedback on Noise 819
16-6. The Effect of Feedback on Impedance Levels 820
16-7. The Effect of Feedback on Bandwidth 825
16-8. The Feedback Pair 826
16-9. Use of Linear Models in General Feedback Amplifier Calculations 830
16-10. Oscillation in Feedback Amplifiers 834
16-11. The Routh-Hurwitz Test for the Location of the Roots of a Polynomial 836
16-12. The Nyquist Criterion for the Stability of a Feedback Amplifier 840
16-13. Further Discussion of Stability 844
16-14. Gain and Phase Margin 848
16-15. Basic Design of Feedback Amplifiers 852
16-16. Corrective Networks 859
16-17. Analysis and Stabilization of a Series-Series Feedback Circuit Triple 863
Problems 865
Bibliography 870

Chapter 17 Bandpass Amplifiers 871

17-1. The Ideal Bandpass Amplifier 871
17-2. The Parallel Resonant Circuit 872
17-3. The Single-Tuned Capacitance-Coupled Amplifier 876
17-4. Impedance Level Control Using a Tapped Inductance 883
17-5. Mutual Inductance-Coupled Single-Tuned Circuits 886
17-6. Double-Tuned Amplifier Circuits 889
17-7. Neutralization 899
17-8. The Superheterodyne Principle 901
17-9. Active Filters—The Thomas Biquad 903

17-10. The Delyiannis Active Filter 909
17-11. Butterworth Filter Characteristics 912
17-12. The Chebyshev Filter Characteristic 918
17-13. The Low-Pass—Bandpass Transformation 922
17-14. Switched-Capacitor Filters 927
Problems 932
Bibliography 937

Chapter 18 Oscillators 939

18-1. RF Oscillators—Criteria for Oscillation 939
18-2. The *RC* Phase Shift Oscillator 948
18-3. The Wien Bridge Oscillator 951
18-4. Linear and Nonlinear Operation of Sinusoidal Oscillators 952
18-5. Frequency Stability 954
18-6. Crystal Oscillators 956
18-7. The Transistor Astable Multivibrator 958
18-8. The Comparator Astable Multivibrator 960
18-9. A Voltage-Controlled Oscillator 964
18-10. The One-Shot or Monostable Multivibrator 966
18-11. Integrated Circuit Waveform Generators—Timers 968
18-12. Clipping and Clamping Circuits 968
Problems 971
Bibliography 974

Chapter 19 Power Supplies 975

19-1. Rectifiers 975
19-2. The Capacitor Filter 979
19-3. Other Filter Circuits 984
19-4. Output Impedance of Power Supplies 987
19-5. Voltage Regulators 988
19-6. Switching Regulators 992
19-7. SCR's, Diacs, and Triacs 999
Problems 1003
Bibliography 1006

Index 1007

Chapter 1

Semiconductors and the *p-n* Junction Diode

Modern semiconductor devices have profoundly changed electronics. A device as simple as a radio has changed from a bulky vacuum tube device to the portable "transistor radio." The modern powerful digital computer would be impractical were it not for integrated circuit technology, which allows thousands of devices to be fabricated on a single chip. Indeed, complete small computers can be built on a single small chip. These microcomputers not only will be used in sophisticated electronic devices, but will find ever increasing use in "commonplace" things. For instance, these small computers can control the engine of an automobile so that its efficiency is greatly improved. They can also ensure the safe operation of a railroad or monitor the recovery room of a hospital.

In this book we shall consider electronic circuits. We shall start with a basic discussion of how electronic devices operate. Fabrication methods, including those for integrated circuits, will also be discussed here. After this we shall study the fundamental ideas used in building electronic circuits and the means for analyzing them. Then, the analysis and design of basic circuits will be discussed. As we progress through the book, the complexity of the circuits will be increased.

Integrated circuit applications will be stressed in this book. However, there are cases where discrete devices are used in practical circuits and these will be discussed when appropriate. A well-educated electrical engineer must understand the operation of integrated circuits thoroughly. Of course, integrated circuits consist of the interconnection of individual devices. Thus, we do not take the viewpoint that a study of discrete devices is unnecessary for those who will work with integrated circuits. For instance, the effect of temperature on the behavior of an individual transistor must be known if the effect of temperature on the behavior of an LSI (large-scale integration) chip, containing many of these transistors, is to be thoroughly understood. In a similar way, the high-frequency model for a discrete transistor is used to obtain the frequency response of an integrated circuit amplifier containing many of these transistors. Thus, we cannot ignore those topics in discrete circuits that improve our understanding of integrated circuits.

Many design examples will be incorporated in the book. The object of these examples will be twofold. They will serve to teach the design of the particular type of circuit under consideration as well as to illustrate some ideas common to many types of design.

We shall start with a basic discussion of semiconductors.

1-1. SEMICONDUCTORS

Modern electronic devices are composed of *semiconductor* materials. In this section we shall discuss some basic ideas of the physics of semiconductors. Subsequently, we shall consider how semiconductors are used in electronic devices. Usually, the atoms of semiconductors that are used in devices are arranged in a regular array called a *crystal*. Such an array for the semiconductor silicon is shown diagrammatically in Fig. 1-1. Materials of valence 4 form such an array. That is, they have four valence electrons, each of which enters into a *covalent bond*, or *electron-pair bond*, with a valence electron of a neighboring atom.

Let us discuss electrical conduction in such a crystal. If each valence electron is bound in its covalent bond pair, then no conduction can take place. If there is to be conduction, then some of the valence electrons must acquire sufficient energy to break their covalent bonds and become free to travel throughout the material. Such electrons are called *free electrons*. Let us consider, in greater detail, the process whereby valence electrons break their bonds.

In a single isolated atom, the electrons cannot possess arbitrary amounts of energy. They can only possess certain allowed energy levels called *discrete energy levels*. There is a maximum number of electrons (which varies from level to level) which can occupy a given energy level. Actually the state of the electron is characterized by a quantum number and no two electrons of an atom can have the same quantum number. When the number of electrons occupying a level is equal to the maximum for that level, then the level is said to be *filled*.

When two atoms are brought together, the energy levels *split*. That is, the two identical levels in each atom now become two distinct new levels, which are very close to the original one. When more atoms are brought together, the energy levels split further.

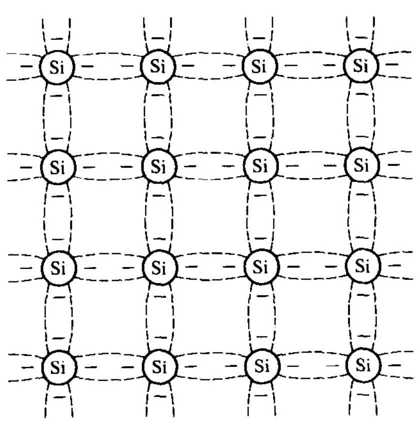

Figure 1-1 A symbolic representation of a silicon crystal array.