

VLSI

Randall L. Geiger

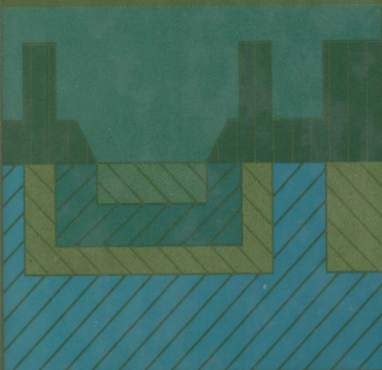
DESIGN TECHNIQUES

Phillip E. Allen

FOR ANALOG AND

Noel R. Strader

DIGITAL CIRCUITS



TN47
G312

一般外借

9062697

9062697

VLSI DESIGN TECHNIQUES FOR ANALOG AND DIGITAL CIRCUITS

Randall L. Geiger

*Department of Electrical Engineering
Texas A&M University*

Phillip E. Allen

*Department of Electrical Engineering
Georgia Institute of Technology*

Noel R. Strader

*MCC
Austin, Texas*



E9062697

McGraw-Hill Publishing Company

New York St. Louis San Francisco Auckland Bogotá Caracas
Hamburg Lisbon London Madrid Mexico Milan
Montreal New Delhi Oklahoma City Paris San Juan
São Paulo Singapore Sydney Tokyo Toronto

This book was set in Times Roman by Publication Services, Inc.
The editors were Alar E. Elken and John M. Morriss;
the production supervisor was Janelle S. Travers.
The cover was designed by Robin Hessel.
Project supervision was done by Publication Services, Inc.
Arcata Graphics/Halliday was printer and binder.

VLSI DESIGN TECHNIQUES FOR ANALOG AND DIGITAL CIRCUITS

Copyright © 1990 by McGraw-Hill, Inc. All rights reserved. Printed in the United States of America. Except as permitted under the United States Copyright Act of 1976, no part of this publication may be reproduced or distributed in any form or by any means, or stored in a data base or retrieval system, without the prior written permission of the publisher.

1 2 3 4 5 6 7 8 9 0 HAL HAL 8 9 4 3 2 1 0 9

ISBN 0-07-023253-9

Library of Congress Cataloging-in-Publication Data

Geiger, Randall L.

VLSI design techniques for analog and
digital circuits.

(McGraw-Hill series in electrical engineering)

Includes index.

1. Integrated circuits--Very large scale
integration--Design and construction. I. Allen, P. E.
(Phillip E.) II. Strader, Noel R. III. Title.

IV. Series.

TK7874.G43 1990

621.381'73

88-37737

ISBN 0-07-023253-9

VLSI DESIGN TECHNIQUES FOR ANALOG AND DIGITAL CIRCUITS

McGraw-Hill Series in Electrical Engineering

Consulting Editor

Stephen W. Director, *Carnegie-Mellon University*

CIRCUITS AND SYSTEMS
COMMUNICATIONS AND SIGNAL PROCESSING
CONTROL THEORY
ELECTRONICS AND ELECTRONIC CIRCUITS
POWER AND ENERGY
ELECTROMAGNETICS
COMPUTER ENGINEERING
INTRODUCTORY
RADAR AND ANTENNAS
VLSI

Previous Consulting Editors

Ronald N. Bracewell, Colin Cherry, James F. Gibbons, Willis W. Harman, Hubert Heffner, Edward W. Herold, John G. Linvill, Simon Ramo, Ronald A. Rohrer, Anthony E. Siegman, Charles Susskind, Frederick E. Terman, John G. Truxal, Ernst Weber, and John R. Whinnery

VLSI

Consulting Editor

Stephen W. Director, *Carnegie-Mellon University*

Elliott: *Microolithography: Process Technology for IC Fabrication*

Geiger, Allen, and Strader: *VLSI Design Techniques for Analog and Digital Circuits*

Offen: *VLSI Image Processing*

Ruska: *Microelectronic Processing: An Introduction to the Manufacture of Integrated Circuits*

Seraphim: *Principles of Electronic Packaging*

Size: *VLSI Technology*

Tsividis: *Operation and Modeling of the MOS Transistor*

Walsh: *Choosing and Using CMOS*

Growing technological requirements and the widespread acceptance of sophisticated electronic devices have created an unprecedented demand for large-scale, complex, integrated circuits. Meeting these demands has required technological advances in materials and processing equipment, significant increases in the number of individuals involved in integrated circuit design, and an increased emphasis on effectively utilizing the computer to aid in the design.

Advances in growing fields, such as Very Large Scale Integrated Circuits (VLSI), generally parallel “graduate level” academic and industrial research efforts. As a result, these concerns quite naturally appear initially in university curricula at the graduate level. However, one must inevitably consider how to present this new material to a wider range of students with less sophisticated backgrounds. Integrated circuit design of LSI and VLSI systems is an area where both the required technical background and demand indicate that the material can and should be introduced at the undergraduate level. It is the purpose of this text to accomplish this objective.

The textbook has grown out of notes prepared for a one-semester senior level course that presents the fundamentals of integrated circuit design. This course has been offered every semester at Texas A&M University since the fall of 1981. Sufficient technical background for this text can be provided by an introductory level circuits course and an introductory digital logic course. Limited knowledge of material covered in an introductory electronics course is also assumed, but those sections requiring this knowledge can be either skipped or be augmented by the instructor without a major loss of continuity.

Each semester, students in the course participate in an integrated circuit design project using the multiproject chip (MPC) approach. Both NMOS and CMOS technologies have been used for the MPC. Process discussions closely parallel those available through the MOSIS program, thus facilitating participation in the MOSIS fabrication program by students who have MOSIS access. Past design projects have been intentionally limited in scope to keep the student’s time

commitments at a reasonable level. Past projects have included ring oscillators, PLAs, flip-flops, simple comparators and operational amplifiers, and 16-bit static RAMs. Although the availability of the processing capability helps provide an appreciation of all the details involved in the design of an integrated circuit, the material in this text is designed to be useful with or without access to foundry services.

The text includes a qualitative discussion of semiconductor processing in order to make the student cognizant of the processing steps required. Beyond this, a set of process parameters used in device modeling are assumed to serve as the interface between the process and the design engineers. The physical relationship between circuit design and actual silicon layout and area is strongly emphasized as is the anticipated performance of the circuit as affected by typical variations in the process parameters, temperature, and so on.

This book adopts the philosophy that the design engineer should be comfortable with either analog or digital circuitry and that the basic differences in the fundamental blocks are minimal. Integrated circuit design is presented as a systematic merging of a set of design rules, device models, and process parameters in a personnel- and area-efficient manner to develop a circuit that meets required electrical specifications. With this approach, the NMOS, CMOS, Bipolar, thick film, and thin film technologies are introduced in parallel. Each of these maintains a uniqueness through a specific set of design rules and device models. Advantages and tradeoffs in regard to area, performance, and processing costs among the technologies are considered. A typical set of design rules and a list of process parameters, sufficient for actual design, are given for each of the processes. These characteristics are used to maintain proper performance perspectives and to make that crucial link between circuit schematic and silicon layout. Since the size of components has been steadily decreasing, the design rules are given in terms of a variable, λ , whenever practical. Although design rules for the MOS and Bipolar processes scale quite well for typical 3, 5, and 8 micron processes, it is emphasized that the actual design rules and process parameters corresponding to the specific fabrication process employed should be adopted.

The ultimate goal of the circuit designer is not a clever circuit schematic or a computer simulation that predicts the circuit works as anticipated, but an efficiently designed physical piece of silicon that satisfies the original specifications. To this end, practical considerations are discussed including limitations of device models, parasitic and nonlinear effects, and clever component placement on the circuit layout, along with their effects on performance.

This book is directed to individuals with no previous integrated circuit design experience who need a working understanding of the subject. The text will also provide a broadened perspective for experienced designers. In addition to the university classroom, this text should find application in industrial training programs, as an interface for groups using or planning to use silicon foundries, and as a resource for the non-semiconductor-based industries that use electronic circuitry and must make the decision of when, if, and how to integrate their systems. It may also serve as a reference book on the subject of integrated circuit design.

Chapter 1 presents an overview of the field of integrated circuit design while focusing on past and present techniques, trends, and performance along with the technological challenges. A discussion of both yield and economics is included in this chapter.

Technology is discussed in Chapter 2. Processing steps are presented from a qualitative point of view, followed by detailed discussions of the NMOS, CMOS, and Bipolar processes along with the thick and thin film technologies. Design rules, layout techniques, and the role of the computer are discussed.

Models for the MOS and Bipolar transistors suitable for design are presented in Chapter 3, as are more sophisticated models necessary for computer simulation. The characteristics of various types of semiconductor passive components are also investigated.

Computer-aided circuit analysis is discussed in Chapter 4. Use of the widely available SPICE program for this purpose is investigated.

Chapter 5 is used to introduce basic analog building blocks.

Building blocks that are useful for constructing analog circuits are discussed in Chapter 6. Both MOS and Bipolar versions are developed in parallel because of the similarity of the circuit topologies.

A digital counterpart to Chapter 5 is presented in Chapter 7. This discussion originates with the inverter, followed by the generation of basic logic gates. Methods of driving large external loads while maintaining acceptable speed are investigated. The emphasis in Chapter 7 is on the MOS technologies because of their widespread acceptance for large digital systems.

In Chapter 8, the design of analog systems is considered. These systems employ some of the basic building blocks discussed in Chapters 5 and 6. Systems considered include A/D and D/A converters, continuous-time filters, switched-capacitor filters, oscillators, multipliers, and modulators.

Digital systems are discussed in Chapter 9. These include PLAs, gate arrays, static and dynamic memories, microprocessors, and systolic arrays.

Design automation is addressed in Chapter 10. The variety of design aids necessary for layout verification is discussed.

Much of the material in the book comes as an outgrowth of the design and testing of integrated circuits that have been included on past MPCs as well as the instruction that has been necessary to prepare students to participate in these designs. The fabrication of the MPCs by Texas Instruments, Inc., and the MOSIS Program is gratefully acknowledged.

McGraw-Hill and the authors would like to thank the following reviewers for their many helpful comments and suggestions: Jorge J. Santiago-Avilés; Steven Bibyk, Ohio State University; David J. Dumin, Clemson University; Yu Hen Hu, University of Wisconsin; David L. Landis, University of South Florida; H.C. Lin, University of Maryland; M.A. Littlejohn, North Carolina State University; R.A. Saleh, University of Illinois; S.M. Sze, AT&T Bell Laboratories; and Herbert Taub, City College of the City University of New York.

*Randall L. Geiger
Phillip E. Allen
Noel R. Strader*

CONTENTS

Preface	xiii
1 Practical Considerations	1
1.0 Introduction	2
1.1 Size and Complexity of Integrated Circuits	4
1.2 The Microelectronics Field	10
1.3 IC Design Process	12
1.4 Economics	16
1.5 Yield	19
1.6 Trends in VLSI Design	28
References	29
Problems	29
2 Technology	32
2.0 Introduction	32
2.1 IC Production Process	32
2.1.1 Processing Steps	33
2.1.2 Packaging and Testing	41
2.2 Semiconductor Processes	42
2.2.1 MOS Processes	46
2.2.1a NMOS Process	49
2.2.1b CMOS Process	55
2.2.1c Practical Process Considerations	59
2.2.2 Bipolar Technology	64
2.2.3 Hybrid Technology	68
2.3 Design Rules and Process Parameters	72
2.4 Layout Techniques and Practical Considerations	78
References	85
Problems	85
Appendixes	95
2A Process Characterization of a Generic NMOS Process	95
2B Process Characterization of a Generic CMOS Process	108

2C	Process Characterization of a Generic Bipolar Process	118
2D	Process Characterization of a Generic Thick Film Process	127
2E	Process Characterization of a Generic Thin Film Process	130
3	Device Modeling	132
3.0	Modeling	132
3.0.1	dc Models	134
3.0.2	Small Signal Models	134
3.0.3	Use of Device Models in Circuit Analysis	139
3.1	MOS Models	143
3.1.1	dc MOSFET Model	144
3.1.2	Small Signal MOSFET Model	158
3.1.3	High Frequency MOSFET Model	161
3.1.4	Measurement of MOSFET Model Parameters	167
3.1.5	Short Channel Devices	171
3.1.6	Subthreshold Operation	174
3.1.7	Operation in the Third Quadrant of the $I_D - V_{DS}$ Plane	177
3.1.8	Modeling Noise Sources in MOSFETs	180
3.1.9	Simple MOSFET Models for Digital Applications	185
3.2	Diode Models	187
3.2.1	dc Diode Model	187
3.2.2	Small Signal Diode Model	190
3.2.3	High-Frequency Diode Model	190
3.3	Bipolar Models	191
3.3.1	dc BJT Model	192
3.3.2	Small Signal BJT Model	202
3.3.3	High-Frequency BJT Model	205
3.3.4	Measurement of BJT Model Parameters	208
3.4	Passive Component Models	210
3.4.1	Monolithic Capacitors	211
3.4.2	Monolithic Resistors	213
3.5	Summary	221
	References	221
	Problems	222
4	Circuit Simulation	237
4.0	Introduction	237
4.1	Circuit Simulation Using Spice	237
4.2	MOSFET Model	240
4.2.1	Level 1 Large Signal Model	241
4.2.2	Level 2 Large Signal Model	244
4.2.3	High-Frequency Model	246
4.2.4	Noise Model of the MOSFET	251
4.2.5	Temperature Dependence of the MOSFET	251
4.3	Diode Model	252
4.3.1	Large Signal Diode Current	253
4.3.2	High-Frequency Diode Model	254
4.4	BJT Model	255
4.4.1	Large Signal BJT Model	256
4.4.2	High-Frequency BJT Model	261

4.4.3	BJT Noise Model	262
4.4.4	Temperature Dependence of the BJT	263
4.5	Summary	264
	References	264
	Problems	265
	Appendixes	271
4A	Mosfet Parameter Definitions	271
4B	Diode Parameter Definitions	280
4C	BJT Parameter Definitions	282
5	Basic Integrated Circuit Building Blocks	287
5.0	Introduction	287
5.1	Switches	289
5.2	Active Resistors	302
5.3	Current Sources and Sinks	318
5.4	Current Mirrors/Amplifiers	333
5.5	Voltage and Current References	354
5.6	Summary	372
	References	372
	Problems	373
	Design Problems	376
6	Amplifiers	378
6.0	Introduction	378
6.1	Inverting Amplifiers	379
6.1.1	General Concepts of Inverting Amplifiers	379
6.1.2	MOS Inverting Amplifiers	389
6.1.3	BJT Inverting Amplifiers	407
6.2	Improving the Performance of Inverting Amplifiers	414
6.2.1	Current-Driven CMOS Cascode Amplifier	416
6.2.2	Voltage-Driven CMOS Cascode Amplifier	418
6.2.3	Improving the Gain of the CMOS Cascode Amplifier	419
6.2.4	The BJT Cascode Amplifier	426
6.3	Differential Amplifiers	431
6.3.1	CMOS Differential Amplifiers	432
6.3.2	BJT Differential Amplifiers	444
6.3.3	Frequency Response of Differential Amplifiers	449
6.3.4	Noise Performance of Differential Amplifiers	452
6.4	Output Amplifiers	454
6.4.1	Output Amplifiers without Feedback	455
6.4.2	Output Amplifiers with Feedback	466
6.5	Operational Amplifiers	473
6.5.1	Characterization of Op Amps	473
6.5.2	The BJT Two-Stage Op Amp	481
6.5.3	The CMOS Two-Stage Op Amp	485
6.5.4	Cascode Op Amps	488
6.5.5	Op Amps with an Output Stage	491
6.5.6	Simulation and Measurement of Op Amps	494

6.6	Comparators	499
6.6.1	Characterization of Comparators	499
6.6.2	High-Gain Comparators	502
6.6.3	Propagation Delay of Two-Stage Comparators	507
6.6.4	Comparators Using Positive Feedback	511
6.6.5	Autozeroing	514
6.7	Summary	518
	References	518
	Problems	519
	Design Problems	524
7	Digital Circuits	525
7.0	Introduction	525
7.1	Design Abstraction	526
7.2	Characteristics of Digital Circuits	528
7.2.1	Logic Level Standards	528
7.2.2	Inverter Pair Characteristics	530
7.2.3	Logic Fan-out Characteristics	532
7.2.4	Digital Logic Analysis	532
7.3	Single-Channel MOS Inverters	534
7.3.1	Basic Inverter	534
7.3.2	Inverter Device Sizing	537
7.3.3	Enhancement-Load versus Depletion-Load Inverters	539
7.4	NMOS NOR and NAND Logic Circuits	540
7.4.1	Basic NMOS NOR Logic Circuits	540
7.4.2	Basic NMOS NAND Logic Circuits	542
7.4.3	Multi-Input NAND and NOR Logic Circuits	543
7.5	Complementary MOS Inverters	544
7.5.1	A Basic CMOS Inverter	546
7.5.2	CMOS Inverter Logic Levels	546
7.5.3	Inverter Device Sizing	548
7.6	CMOS Logic Gates	551
7.6.1	CMOS NOR Logic Gate	551
7.6.2	CMOS NAND Logic Gate	553
7.6.3	Multi-Input CMOS Logic Gates	556
7.7	Transmission Gates	558
7.7.1	NMOS Pass Transistor	559
7.7.2	CMOS Transmission Gate	562
7.8	Signal Propagation Delays	564
7.8.1	Ratio-Logic Model	565
7.8.2	Process Characteristic Time Constant	570
7.8.3	Inverter-Pair Delay	570
7.8.4	Superbuffers	573
7.8.5	NMOS NAND and NOR Delays	575
7.8.6	Enhancement versus Depletion Loads	578
7.8.7	CMOS Logic Delays	579
7.8.8	Interconnection Characteristics	582
7.9	Capacitive Loading Considerations	584
7.9.1	Capacitive Loading	584
7.9.2	Logic Fan-out Delays	585

7.9.3	Distributed Drivers	587
7.9.4	Driving Off-Chip Loads	588
7.9.5	Cascaded Drivers	590
7.10	Power Dissipation	593
7.10.1	NMOS Power Dissipation	595
7.10.2	CMOS Power Dissipation	597
7.11	Noise in Digital Logic Circuits	599
7.11.1	Resistive Noise Coupling	599
7.11.2	Capacitive Noise Coupling	601
7.11.3	Definition of Noise Margins	602
7.11.4	NMOS Noise Margins	603
7.11.5	CMOS Noise Margins	605
7.12	Summary	607
	References	608
	Problems	608
8	Analog Systems	612
8.0	Introduction	612
8.1	Analog Signal Processing	612
8.2	Digital-to-Analog Converters	615
8.2.1	Current-Scaling D/A Converters	623
8.2.2	Voltage-Scaling D/A Converters	626
8.2.3	Charge-Scaling D/A Converters	629
8.2.4	D/A Converters Using Combinations of Scaling Approaches	633
8.2.5	Serial D/A Converters	638
8.3	Analog-to-Digital Converters	642
8.3.1	Serial A/D Converters	648
8.3.2	Successive Approximation A/D Converters	651
8.3.3	Parallel A/D Converters	659
8.3.4	High-Performance A/D Converters	664
8.3.5	Summary	671
8.4	Continuous-Time Filters	673
8.4.1	Low-Pass Filters	674
8.4.2	High-Pass Filters	685
8.4.3	Bandpass Filters	688
8.5	Switched Capacitor Filters	692
8.5.1	Resistor Realization	693
8.5.2	Passive RLC Prototype Switched Capacitor Filters	703
8.5.3	Z-Domain Synthesis Techniques	716
8.6	Analog Signal Processing Circuits	729
8.6.1	Precision Breakpoint Circuits	729
8.6.2	Modulators and Multipliers	735
8.6.3	Oscillators	747
8.6.4	Phase-Locked Loops	762
8.7	Summary	765
	References	770
	Problems	773
9	Structured Digital Circuits and Systems	778
9.0	Introduction	778
9.1	Random Logic versus Structured Logic Forms	779

9.2	Programmable Logic Arrays	783
9.2.1	PLA Organization	784
9.2.2	Automatic PLA Generation	790
9.2.3	Folded PLAs	791
9.2.4	Large PLAs	792
9.3	Structured Gate Layout	793
9.3.1	Weinberger Arrays	794
9.3.2	Gate Matrix Layout	796
9.4	Logic Gate Arrays	799
9.5	MOS Clocking Schemes	805
9.6	Dynamic MOS Storage Circuits	808
9.6.1	Dynamic Charge Storage	808
9.6.2	Simple Shift Register	811
9.6.3	Other Shift Registers	814
9.7	Clocked CMOS Logic	815
9.7.1	C ² MOS	815
9.7.2	Precharge-Evaluate Logic	817
9.7.3	Domino CMOS	819
9.8	Semiconductor Memories	821
9.8.1	Memory Organization	822
9.9	Read-Only Memory	824
9.9.1	Erasable Programmable Read-Only Memory	825
9.9.2	Electrically Erasable Programmable Read-Only Memory	826
9.10	Static RAM Memories	827
9.11	Dynamic RAM Memory	835
9.12	Register Storage Circuits	839
9.12.1	Quasi-Static Register Cells	840
9.12.2	A Static Register Cell	842
9.13	PLA-Based Finite-State Machines	845
9.14	Microcoded Controllers	848
9.15	Microprocessor Design	853
9.15.1	Data Path Description	856
9.15.2	Barrel Shifter	857
9.15.3	Arithmetic Logic Unit	858
9.15.4	Microcoded Controller	860
9.16	Systolic Arrays	861
9.16.1	Systolic Matrix Multiplication	861
9.16.2	General Linear System Solver	862
9.16.3	Bit-Serial Processing Elements	863
9.17	Summary	866
	References	866
	Problems	867
10	Design Automation and Verification	872
10.0	Introduction	872
10.1	Integrated Circuit Layout	873
10.1.1	Geometrical Specification Languages	875
10.1.2	Layout Styles	878
10.2	Symbolic Circuit Representation	880
10.2.1	Parameterized Layout Representation	880
10.2.2	Parameterized Module Generation	883

10.2.3	Graphical Symbolic Layout	884
10.2.4	Logic Equation Symbology	885
10.3	Computer Check Plots	889
10.4	Design Rule Checks	894
10.4.1	Geometrical Design Rules	894
10.4.2	Computer Design Rule Checks	897
10.4.3	Design Rule Checker Output	898
10.5	Circuit Extraction	901
10.5.1	A Simple Circuit Extraction Algorithm	902
10.5.2	Circuit Extractor Output	903
10.5.3	Interface to Other Programs	908
10.6	Digital Circuit Simulation	908
10.7	Logic and Switch Simulation	909
10.7.1	Logic-level Simulation	909
10.7.2	Switch-level Simulation	913
10.7.3	Hardware Logic Simulation	917
10.8	Timing Analysis	918
10.8.1	Timing Analysis Methodology	918
10.8.2	Timing Analysis Tools	919
10.9	Register-Transfer-Level Simulation	923
10.9.1	Simple RTL	923
10.9.2	ISPS Specification and Simulation	925
10.9.3	RTL Simulation with LISP	926
10.10	Hardware Design Languages	929
10.10.1	EDIF Design Description	930
10.10.2	EDIF Net List View of Full Adder	931
10.10.3	EDIF Mask Layout View of Full Adder	931
10.10.4	VHDL Design Description	935
10.11	Algorithmic Layout Generation	938
10.11.1	Bristle Blocks Silicon Compiler	938
10.11.2	MacPitts Silicon Compiler	941
10.11.3	Commercial Silicon Compilers	943
10.12	Summary	944
	References	945
	Problems	946
	Index	951

CHAPTER 1

PRACTICAL CONSIDERATIONS

The field of VLSI design is a resource-intense engineering discipline. Project and product definitions are economically motivated, and competition on a worldwide basis is very keen. The market potential for innovative designs is very large, but the market window is often short due to both competition and changing consumer demands. Financial gain potential for both individuals and companies in this field is phenomenal, but the risks can also be very large. Some of the most advanced equipment and CAD resources available in any discipline are focused toward VLSI design and production; this focus makes the field very dynamic but also necessitates a continuing training and learning effort on the part of the design engineers to remain current and productive in this field.

It is our goal in this book to introduce basic electronic principles needed by the integrated circuit designer and to discuss engineering tradeoffs and practical considerations that are necessary for the student to make the transition from the classroom to industry as an integrated circuit designer. Although it is impossible to discuss all the practical aspects considered by experienced designers, it is our hope that through the discussions and comments presented in this book, the student will develop a sense of what types of practical questions must be addressed throughout the design process.

This chapter gives a brief historical overview, followed by a discussion of some of the terminology and jargon specific to the VLSI design field. (We have chosen to adopt the jargon used in the field because this is the language used by VLSI designers to communicate.) Size and complexity perspectives of VLSI circuits are discussed, and the basic types of processes used in IC and VLSI design are qualitatively summarized. The design process itself and the tools available to the designer are covered. Finally, a brief discussion of economics is presented to give the reader a basic appreciation of design costs and fabrication costs of

integrated circuits. Included is a simple discussion of the relationship between yield and chip area, which often is the key factor in determining whether a design will be economically viable.

1.0 INTRODUCTION

Historically, several events trace the evolution of what is currently termed VLSI technology. In the early 1930s, theoretical developments by Lilienfeld¹ and Heil² discussed the predecessor to what is now commonly called the field effect transistor (FET). Technological challenges delayed the practical utilization of this device for nearly three decades. In 1947 and 1948, three researchers at Bell Laboratories—Brattin, Bardeen, and Shockley—introduced the bipolar junction transistor (BJT). This development marked the practical beginning of the microelectronics industry. For the next 15 years, large numbers of different BJTs were produced and applied in a wide range of instrumentation systems. The BJTs replaced vacuum tubes in many applications and provided the impetus for a host of new electronic systems.

In the summer of 1958 Jack Kilby, an engineer at Texas Instruments, invented the first integrated circuit. Early the following year Robert Noyce of Fairchild independently reported on a procedure that more closely resembles integrated circuits of today. The specific details of Kilby's circuit are inconsequential, but the impact of his approach has been phenomenal.^{3,4} The work of Kilby and Noyce marked the beginning of what has become the field of VLSI design.

Germanium was widely used as a semiconductor in some of the early discrete devices. Silicon has been the dominant semiconductor material used for integrated circuit fabrication for the past two decades, and most experts agree that it will remain dominant for the next decade. Since over 25% of the earth's crust is made of silicon, a real silicon shortage is highly unlikely! Other materials, such as gallium arsenide, are gaining acceptance in niche markets, which may be quite profitable.

Improvements in technology—ranging from improvements in materials and photolithography to advancements in processing—have been propelled by the significant financial gains offered to groups that excel in this area. Many integrated circuits of today contain a very large number of transistors, over 1 million in some designs. Conventional methods for circuit design that involved iteration at the breadboard level proved impractical for designing integrated circuits. This is due to poor designer productivity and the high cost associated with fabricating ICs. Methods of efficiently handling large quantities of design data were needed. Models of transistors that accurately predict experimental performance were required. Methods were needed for increasing designer productivity and reducing the design cycle time as the size and complexity of circuits increased.

The tools available now to the IC designer are very powerful and dynamic. Most require the use of large computers or, more recently, powerful graphics-intensive workstations. The continued investment in both hardware and software needed for current integrated circuit design is high but is also crucial to remaining competitive. As powerful and dynamic as these tools may be, the fierce competition in the marketplace has resulted in the evolution of user-friendly software