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**VLSI  
TECHNOLOGY**

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*Edited by*  
**S. M. Sze**

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# VLSI TECHNOLOGY

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*Edited by*  
**S. M. Sze**  
*Bell Laboratories, Incorporated*  
*Murray Hill, New Jersey*

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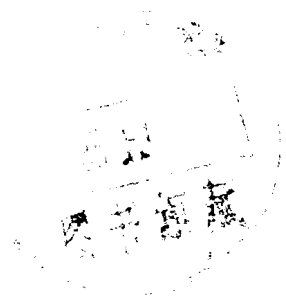
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# PREFACE

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*VLSI Technology* describes the theoretical and practical aspects of the most advanced state of electronics technology—very-large-scale integration (VLSI). From crystal growth to reliability testing, the reader is presented with all the major steps in the fabrication of VLSI circuits. In addition many broader topics, such as process simulation and diagnostic techniques, are considered in detail. Each chapter describes one aspect of VLSI processing. The chapter's introduction provides a general discussion of the topic, and subsequent sections present the basic science underlying individual process steps, the necessity for particular steps in achieving required parameters, and the trade-offs in optimizing device performance and manufacturability. The problems at the end of each chapter form an integral part of the development of the topic.

The book is intended as a textbook for senior undergraduate or first-year graduate students in electrical engineering, applied physics, and materials science; it assumes that the reader has already acquired an introductory understanding of the physics and technology of semiconductor devices. Because it elaborates on IC processing technology in a detailed and comprehensive manner, it can also serve as a reference for those actively involved in integrated circuit fabrication and process development.

This text began in 1979 as a set of lecture notes prepared by the contributing authors for an in-hours continuing education course at Bell Laboratories. The course, called "Silicon Integrated Circuit Processing," has been given to hundreds of engineers and scientists engaged in research, development, fabrication, and application work of ICs. We have substantially expanded and updated the lecture notes to include the most advanced and important topics in VLSI processing.

In the course of writing *VLSI Technology*, many people have assisted us and offered their support. We would first like to express our appreciation to the management of Bell Laboratories and Western Electric for providing the environment in which we worked on the book. Without their support, this book could not have been written. We have benefited significantly from suggestions made by the reviewers: Drs. L. P. Adda, C. M. Bailey, K. E. Benson, J. E. Berthold, J. B. Bindell, J. H. Bruning, R. E. Caffrey, C. C. Chang, D. L. Flamm, G. K. Herb, R. E. Howard,

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*S. M. Sze*



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# CONTENTS

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List of Contributors	xi
Preface	xiii
Introduction	1
<b>Chapter 1</b> Crystal Growth and Wafer Preparation	9
C. W. Pearce	
1.1 Introduction	9
1.2 Electronic-Grade Silicon	10
1.3 Czochralski Crystal Growing	14
1.4 Silicon Shaping	32
1.5 Processing Considerations	42
1.6 Summary and Future Trends	46
References	47
Problems	49
<b>Chapter 2</b> Epitaxy	51
C. W. Pearce	
2.1 Introduction	51
2.2 Vapor-Phase Epitaxy	52
2.3 Molecular Beam Epitaxy	74
2.4 Silicon on Insulators	80
2.5 Epitaxial Evaluation	85
2.6 Summary and Future Trends	88
References	88
Problems	92

<b>Chapter 3</b>	<b>Dielectric and Polysilicon Film Deposition</b>	<b>93</b>
	A. C. Adams	
3.1	Introduction	93
3.2	Deposition Processes	94
3.3	Polysilicon	99
3.4	Silicon Dioxide	106
3.5	Silicon Nitride	119
3.6	Plasma-Assisted Depositions	120
3.7	Other Materials	124
3.8	Summary and Future Trends	125
	References	126
	Problems	128
<b>Chapter 4</b>	<b>Oxidation</b>	<b>131</b>
	L. E. Katz	
4.1	Introduction	131
4.2	Growth Mechanism and Kinetics	132
4.3	Oxidation Techniques and Systems	149
4.4	Oxide Properties	153
4.5	Redistribution of Dopants at Interface	157
4.6	Oxidation of Polysilicon	159
4.7	Oxidation-Induced Defects	160
4.8	Summary and Future Trends	164
	References	165
	Problems	167
<b>Chapter 5</b>	<b>Diffusion</b>	<b>169</b>
	J. C. C. Tsai	
5.1	Introduction	169
5.2	Models of Diffusion in Solids	170
5.3	Fick's One-Dimensional Diffusion Equations	172
5.4	Atomistic Diffusion Mechanisms	177
5.5	Measurement Techniques	184
5.6	Diffusivities of B, P, As, and Sb	193
5.7	Diffusion in SiO <sub>2</sub>	204
5.8	Fast Diffusants in Silicon	206
5.9	Diffusion in Polycrystalline Silicon	207
5.10	Diffusion Enhancements and Retardations	209
5.11	Summary and Future Trends	214
	References	215
	Problems	217

<b>Chapter 6</b>	<b>Ion Implantation</b>	219
	T. E. Seidel	
6.1	Introduction	219
6.2	Ion Implant System and Dose Control	220
6.3	Ion Ranges	224
6.4	Disorder Production	235
6.5	Annealing of Implanted Dopant Impurities	242
6.6	Shallow Junctions (As, BF <sub>2</sub> )	253
6.7	Minority-Carrier Effects	255
6.8	Gettering	255
6.9	Effects in VLSI Processing	258
6.10	Summary and Future Trends	260
	References	261
	Problems	264
<b>Chapter 7</b>	<b>Lithography</b>	267
	D. A. McGillis	
7.1	Introduction	267
7.2	The Lithographic Process	268
7.3	Optical Lithography	274
7.4	Electron Beam Lithography	281
7.5	X-Ray Lithography	287
7.6	Other Lithography Techniques	294
7.7	Summary and Future Trends	298
	References	299
	Problems	300
<b>Chapter 8</b>	<b>Dry Etching</b>	303
	C. J. Mogab	
8.1	Introduction	303
8.2	Pattern Transfer	304
8.3	Low-Pressure Gas Discharges	312
8.4	Plasma-Assisted Etching Techniques	317
8.5	Control of Etch Rate and Selectivity	321
8.6	Control of Edge Profile	330
8.7	Side Effects	334
8.8	Dry Etching Processes for VLSI Technology	336
8.9	Summary of Future Trends	341
	References	342
	Problems	344

<b>Chapter 9</b>	<b>Metallization</b>	347
	D. B. Fraser	
9.1	Introduction	347
9.2	Methods of Physical Vapor Deposition	354
9.3	Problems Encountered in Metallization	361
9.4	Metallization Failure	367
9.5	Silicides for Gates and Interconnections	372
9.6	Corrosion and Bonding	380
9.7	Future Trends	381
	References	381
	Problems	383
<b>Chapter 10</b>	<b>Process Simulation</b>	385
	W. Fichtner	
10.1	Introduction	385
10.2	Epitaxy	385
10.3	Ion Implantation	390
10.4	Diffusion and Oxidation	397
10.5	Lithography	408
10.6	Etching and Deposition	428
10.7	Device Simulation	439
10.8	Summary and Future Trends	441
	References	441
	Problems	443
<b>Chapter 11</b>	<b>VLSI Process Integration</b>	445
	L. C. Parrillo	
11.1	Introduction	445
11.2	Basic Considerations for IC Processing	446
11.3	Bipolar IC Technology	448
11.4	NMOS IC Technology	461
11.5	Complementary MOS IC Technology	478
11.6	Miniaturizing VLSI Circuits	490
11.7	Modern IC Fabrication	497
11.8	Summary and Future Trends	499
	References	500
	Problems	504
<b>Chapter 12</b>	<b>Diagnostic Techniques</b>	507
	R. B. Marcus	
12.1	Introduction	507
12.2	Morphology Determination	508

12.3	Chemical Analysis	520
12.4	Crystallographic Structure and Mechanical Properties	533
12.5	Electrical Mapping	539
12.6	Summary and Future Trends	546
	References	547
	Problems	549
<b>Chapter 13</b>	<b>Assembly Techniques and Packaging</b>	<b>551</b>
	C. A. Steidel	
13.1	Introduction	551
13.2	Wafer Separation and Sorting	552
13.3	Die Interconnection	552
13.4	Package Types and Fabrication Technologies	570
13.5	Special Package Considerations	582
13.6	Package Application Considerations	584
13.7	Summary and Future Trends	595
	References	595
	Problems	598
<b>Chapter 14</b>	<b>Yield and Reliability</b>	<b>599</b>
	W. J. Bertram	
14.1	Introduction	599
14.2	Mechanisms of Yield Loss in VLSI	600
14.3	Modeling of Yield Loss Mechanisms	603
14.4	Reliability Requirements for VLSI	612
14.5	Mathematics of Failure Distributions, Reliability, and Failure Rates	614
14.6	Common Distribution Functions	617
14.7	Accelerated Testing	624
14.8	Failure Mechanisms	632
14.9	Summary and Future Trends	635
	References	636
	Problems	637
	<b>Appendixes</b>	<b>639</b>
A	Properties of Silicon	639
B	List of Symbols	641
C	International System of Units	643
D	Physical Constants	644
	<b>Index</b>	<b>645</b>

### GROWTH OF THE INDUSTRY

The electronics industry in the United States has grown rapidly in recent years, with factory sales increasing by a factor of 10 since the early 1960s. [See Fig. 1, curve (a).<sup>1, 2</sup>] Electronics sales, which were \$114 billion in 1981, are projected to increase at an average annual rate of 15% and finally reach \$400 billion by 1990. The integrated circuit (IC) market has increased at an even higher rate than electronic sales [see Fig. 1, curve (b)]. IC sales in the United States were \$6.6 billion in 1981 and are expected to grow by 25% annually, reaching \$50 billion by 1990. The main impetuses for such phenomenal market growth are the intrinsic pervasiveness of electronic products and the continued technological breakthroughs in integrated circuits. The world market of electronics (about twice the size of the US market) will grow at a comparable rate.<sup>3</sup> In 10 years, it will rival the automobile, chemical, and steel industries in sales volume.

Figure 2 shows the sales of major IC groups and how sales have changed in recent years.<sup>1</sup> In the 1960s the IC market was broadly based on bipolar transistors. Since 1975, however, digital MOS ICs have prevailed. At present, even the intrinsic speed advantage of bipolar transistors is being challenged by MOSFETs. Because of the advantages in device miniaturization, low power dissipation, and high yield, by 1990 digital MOS ICs will dominate the IC market and capture a major market share of all semiconductor devices sold. This book, therefore, emphasizes MOS-related VLSI technology.

### DEVICE MINIATURIZATION

Figure 3, curve (a), shows the exponential growth of the number of components per IC chip.<sup>4</sup> Note that IC complexity has advanced from small-scale integration (SSI) to medium-scale integration (MSI), to large-scale integration (LSI), and finally to very-large-scale integration (VLSI), which has  $10^5$  or more components per chip.

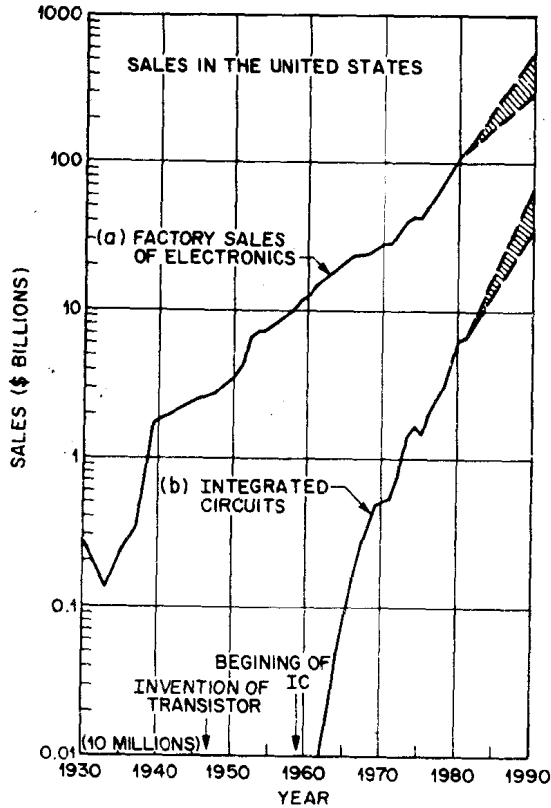


Fig. 1 (a) Factory sales of electronics in the United States for the 52 years between 1930 and 1981 and projected to 1990. (b) Integrated circuit market in the United States for the 20 years between 1962 and 1981 and projected to 1990. (After Refs. 1 and 2.)

Although the rate of growth has slowed down in recent years because of difficulties in defining, designing, and processing complicated chips, a complexity of over 1 million devices per chip will be available before 1990.

The most important factor in achieving such complexity is the continued reduction of the minimum device dimension [see Fig. 3, curve (b)]. Since 1960, the annual rate of reduction has been 13%; at that rate, the minimum feature length will shrink from its present length of 2  $\mu\text{m}$  to 0.5  $\mu\text{m}$  in 10 years.

Device miniaturization results in reduced unit cost per function and in improved performance. Figure 4, curve (a), gives an example of the cost reduction. The cost per bit of memory chips has halved every 2 years for successive generations of random-access memories.<sup>5</sup> By 1990 the cost per bit is expected to be as low as ~ 1 millicent for a 1-megabit memory chip. Similar cost reductions are expected for logic ICs.

As device dimension decreases, the intrinsic switching time in MOSFETs decreases linearly. (The intrinsic delay is given approximately by the channel length

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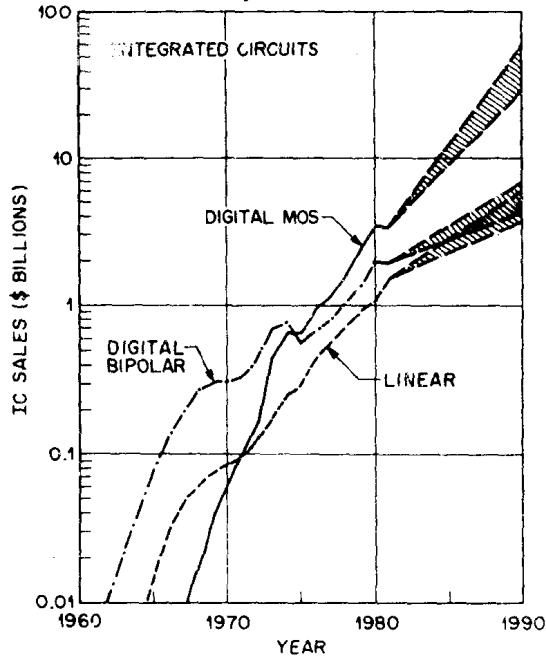


Fig. 2 Sales of major IC groups in the United States. (After Ref. 1.)

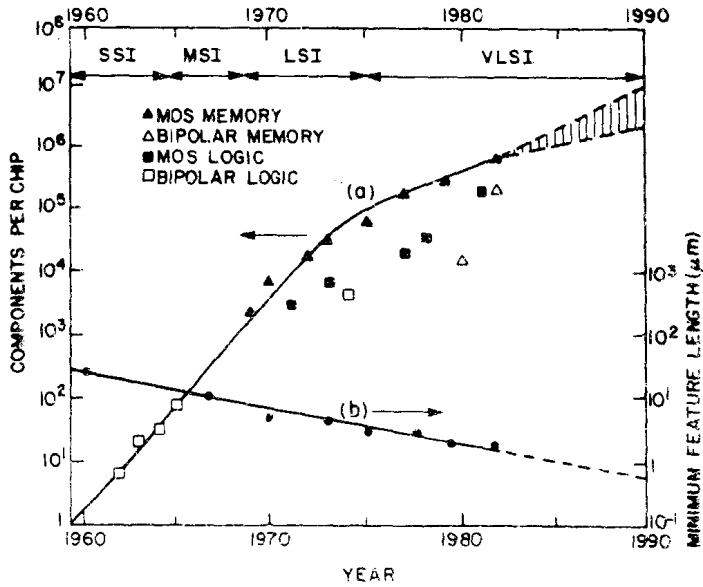
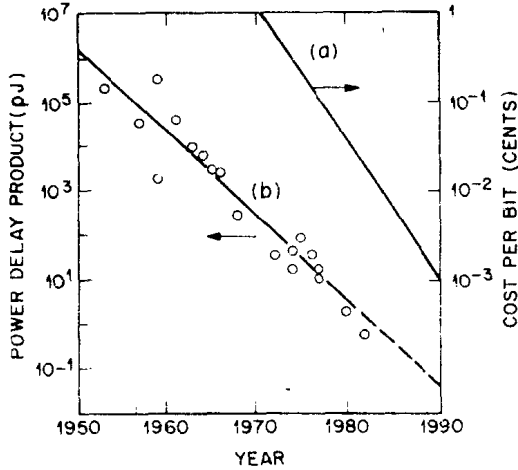


Fig. 3 (a) Exponential growth of the number of components per IC chip. (After Moore, Ref. 4.)  
 (b) Exponential decrease of the minimum device dimensions.





**Fig. 4** (a) Reduction of cost per bit of RAM chips. (After Noyce, Ref. 5.) (b) Power-delay product per logic gate versus year. (After Keyes, Ref. 6.)

divided by the carrier velocity.) The device speed has improved by two orders of magnitude since 1960. Higher speeds lead to expanded IC functional throughput rates. In the future, digital ICs will be able to perform data processing, numerical computation, and signal conditioning at gigabit-per-second rates. Another benefit of miniaturization is the reduction of power consumption. As the device becomes smaller, it consumes less power. Therefore, device miniaturization also reduces the energy used for each switching operation. Figure 4, curve (b), shows the trend of this energy consumption, called the power-delay product.<sup>6</sup> The energy dissipated per logic gate has decreased by over four orders of magnitude since 1960.

## INFORMATION AGE

Figure 5 shows four periods of change in the electronics industry in the United States. Each period exhibits normal life-cycle characteristics<sup>7</sup> (i.e., from incubation to rapid growth, to saturation, and finally to decline). The development of the vacuum tube in 1906 and the invention of transistors<sup>8</sup> in 1947 opened the field of electronic circuit designs. The development of integrated circuits<sup>9</sup> in 1959 led to a new generation of logic families. Since 1975, the beginning of VLSI, the frontier has moved to system organization of ICs and the associated software designs.

Many system-oriented VLSI chips, such as speech analysis/recognition and storage circuits, will be built in response to the enormous market demand for sophisticated electronic systems to handle the growing complexities of the Information Age.<sup>10,11</sup> In this age a major portion of our work force can be called "information workers"; they are involved in gathering, creating, processing, disseminating, and using information. Figure 6 shows the changing composition of the work force in the