VLSI TECHNOLOGY

Edited by
S. M. Sze

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PREFACE

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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INTRODUCTION

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).[1,2]] 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.[3] 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.[1] 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.[4] 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.

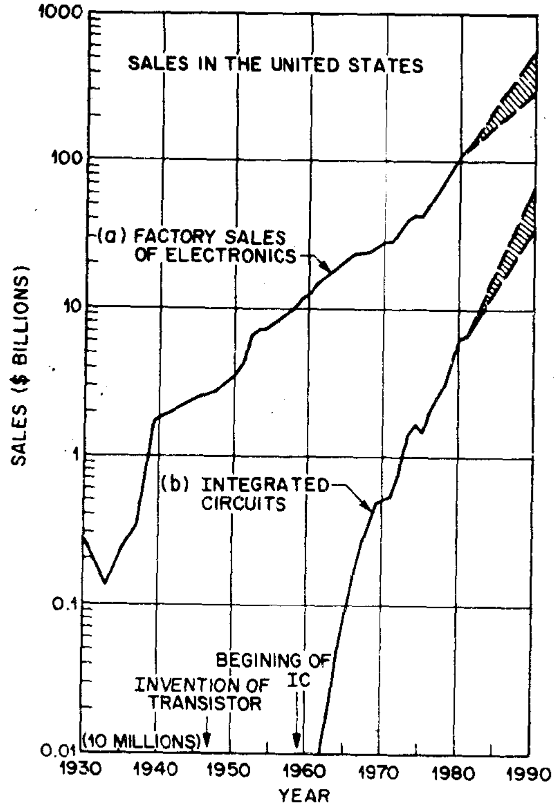

Fig. 1 (a) Factory sales of electronics in the United States for the 52 years between 1930 and 1981 and projected to 1990. (b) Integrated circuit market in the United States for the 20 years between 1962 and 1981 and projected to 1990. *(After Refs. 1 and 2.)*

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 μm to 0.5 μm 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.[5] 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

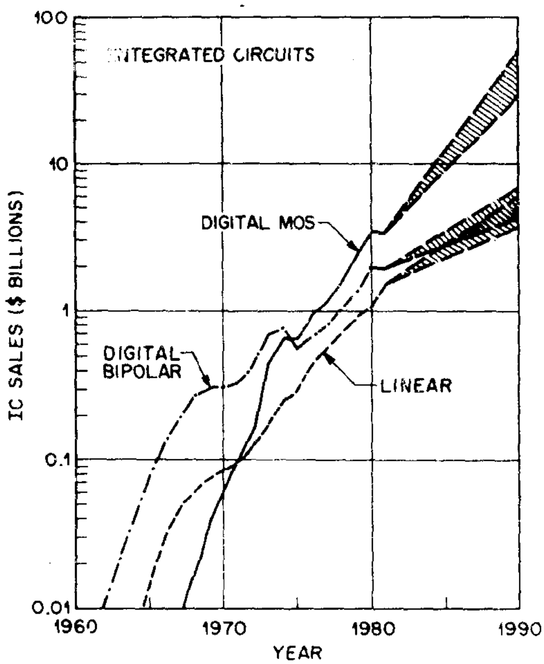

Fig. 2 Sales of major IC groups in the United States. *(After Ref. 1.)*

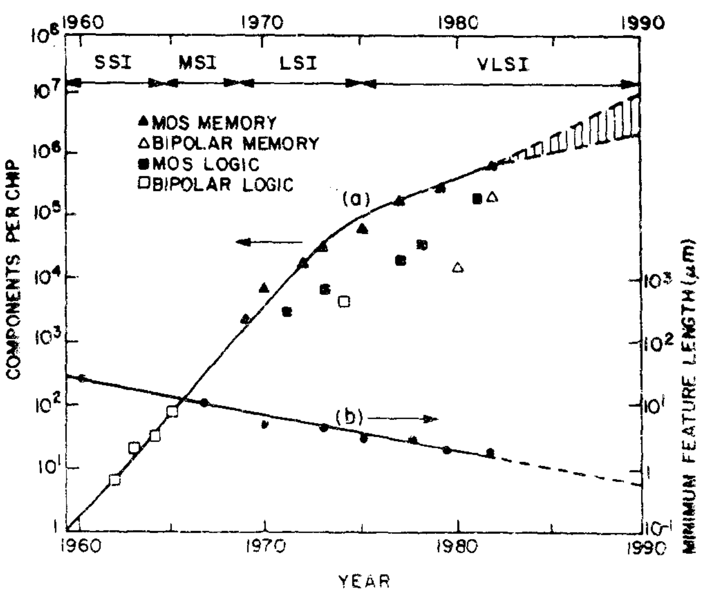

Fig. 3 (a) Exponential growth of the number of components per IC chip. *(After Moore, Ref. 4.)* (b) Exponential decrease of the minimum device dimensions.

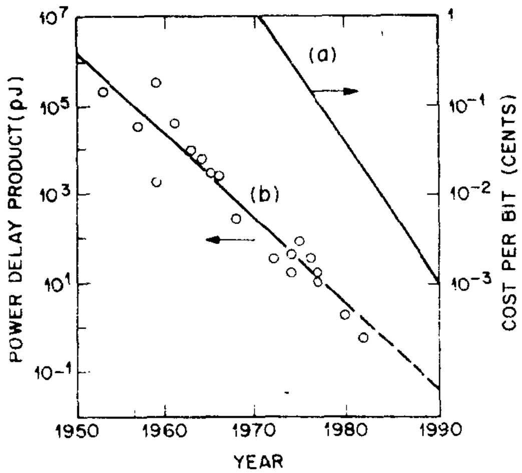

Fig. 4 (a) Reduction of cost per bit of RAM chips. *(After Noyce, Ref. 5.)* (b) Power-delay product per logic gate versus year. *(After Keyes. Ref. 6.)*

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.[6] 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[7] (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[8] in 1947 opened the field of electronic circuit designs. The development of integrated circuits[9] 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.[10, 11] 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