# VLSI

# DESIGN TECHNIQUES FOR ANALOG AND DIGITAL CIRCUITS


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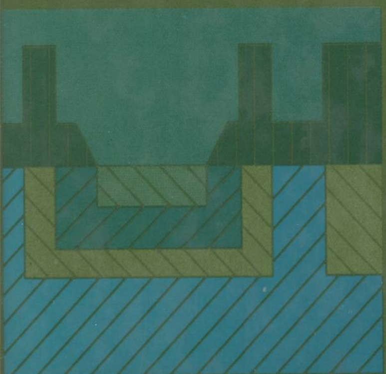

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## VLSI

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# PREFACE

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 concents 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 sophsticated 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 foundary 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, $\lambda$, 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.

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# 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 Lilienfeld[1] and Heil[2] 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 Schockley—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-intense 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