CMOS Analog and Mixed-Signal Circuit Design

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CMOS Analog and Mixed-Signal Circuit Design

Practices and Innovations

Arjuna Marzuki

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Preface

The purpose of this book is to provide a complete working knowledge of the Complementary Metal-Oxide Semiconductor (CMOS) analog and mixed-signal circuit design, which can be applied for System on Chip (SOC) or Application-Specific Standard Product (ASSP) development. The assumed background of the reader is knowledge of linear circuits, discrete concepts, microelectronic devices, and Very Large-Scale Integration (VLSI) systems. The [first chapter](#) covers an introduction to CMOS analog and mixed-signal circuit design. This chapter gives an overview of the subject of analog and mixed-signal circuit design, which is an introduction to analog and digital integrated circuit design concepts. Three-dimensional factors, such as technology, circuit topology, and methodology are described in this chapter. The trade-offs concept is also discussed in this chapter.

CMOS technology continues to be the dominant technology for fabricating integrated circuits. This book will cover basic devices such as the Metal-Oxide Semiconductor Field-Effect Transistor (MOSFET), with both long and short-channel operations. This topic is covered in Chapter 2 solely to provide a MOSFET understanding to the readers. The understanding of the MOSFET is very crucial in CMOS circuit design. Photo devices and other related devices are also discussed in this chapter. A new topic such as the fitting ratio is included to discuss the design “transfer” approach. This approach is useful for practicing engineers.

Seven chapters focus on the CMOS analog and mixed-signal circuit design. There are amplifiers, low power amplifiers, voltage regulator-reference, data converters, dynamic analog circuits, color and image sensors, and peripheral (oscillators and Input/Output (I/O)) circuits. Two chapters (Chapters 6 and 7) out of seven chapters emphasize the mixed-signal circuit design. Chapter 8 focuses on the examples of CMOS analog and mixed-signal circuit designs, such as color and image sensors. One chapter is focused on the Integrated Circuit (IC) layout and packaging. The knowledge of the IC layout and packaging is critical in the development of the CMOS circuit design, especially for analog and mixed-signal IC products.

One of the aims of this book is to provide a text for an introductory course on CMOS analog circuit design for senior undergraduates and graduate students. Many examples and exercises are provided in this book. Some of the circuits are ready to be simulated using the Electronic Design Automation (EDA) tool such as Simulation Program with Integrated Circuit Emphasis (SPICE). Chapters 2 and 3 are derived from the analog IC design senior undergraduate course at the Universiti Sains Malaysia. These two chapters provide a quick and complete understanding of CMOS analog circuit design.

This book presents practical methods working engineers have encountered in the design of analog and mixed-signal circuits. Chapters 4–9 have been arranged with earlier topics for the working engineers, while the remaining topics are for the graduates or researchers. The principles and concepts discussed should never

become outdated even though technology changes. For researchers, innovation topics, such as the current-reuse technique and subthreshold operation, are important for low power applications. Diodeless voltage reference and dynamic element matching are also relevant for the researchers. This book surely provides design and layout examples that will be immediately useful in commercial ICs.

Acknowledgments

I am indebted to those who helped us in bringing this book through the process of idea to reality.

I also wish to express our appreciation to the School of Electrical and Electronic Engineering of Universiti Sains Malaysia. Finally, the success of this book would not have been possible without the kind assistance provided by my graduate students.

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Arjuna joined Hewlett-Packard as an R&D engineer in Wireless Semiconductor Division in 1997. His main jobs were to design Radio Frequency (RF) and radio frequency integrated circuit (RFIC) products. Such products were high-frequency transistors, RF gain blocks, I/Q demodulator, etc. He then later joined IC Microsystems Sdn. Bhd. in Cyberjaya, Selangor, Malaysia, as IC design staff engineer. In the company, he involved in designing 12/10/8 bits digital-to-analog converter ICs and family of RFIC devices. He also managed to secure MYR 3.5 million MGS fund for RFIC device research and development/commercialization. He later joined Agilent Technologies as IC design engineer/manager in Optical Product Division. His main jobs were to lead the analog design group, which was assigned to design operational amplifiers, band-gap circuits, data-converters, I/Os, power-on reset, etc. A small contribution by the group was “Industry’s 1st Digital Color Sensor IC with I/O via 2-wire Serial Interface,” which was released in February 2006 by Avago Technologies. He has been granted 1 US patent and has developed more than 20 commercial products during his employment with Hewlett-Packard/Agilent Technologies and IC Microsystems.

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1 CMOS Analog and Mixed-Signal Circuit Design

An Overview

1.1 INTRODUCTION

The analog circuit employs the analog signal, while the digital circuit employs the signal that is defined only at discrete values of amplitude. A mixed-signal integrated circuit is a combination of analog and digital integrated circuits. This book proposes the concept of a signal path idea for circuit design insight. This book covers the practices and research topics of the analog and mixed-signal integrated circuits.

Design is a process to achieve at least three outputs or objectives, namely, electrical specification, circuit schematic, and device parameters, such as Width/Length (W/L) ratio. An analysis of a circuit is required to be done before the circuit is finalized. Using modern tools in designing a circuit is unavoidable, however, designers need to realize the modern tools are only used to validate the performance of the circuit. The “novelty” or “robustness” of the circuit solely depended on the designers themselves.

This book is not about design procedures. This book stresses the concept of design, and does not stress the mathematical. Nevertheless, the analysis does require or use mathematical equations, so a balance of concept and equations will be applied throughout this book.

1.2 NOTATION, SYMBOL, AND TERMINOLOGY

All notations are kept simple for easier understanding. These notations are related to signals or concept. A signal is any detectable value of voltage or current. A signal could provide information about the state of the behavior of an integrated circuit. A small signal symbol uses a lower-case character, while a large signal symbol uses a capital case character. [Figure 1.1](#) shows the basic transistor symbols used in this book. An abbreviation is followed with a full name for quick reference. Important terminology is italic for easier reference.

FIGURE 1.1 Circuit symbols for *n*-channel and *p*-channel enhancement type of Metal-Oxide Semiconductor Field-Effect Transistors (MOSFETs).

1.3 TECHNOLOGY, CIRCUIT TOPOLOGY, AND METHODOLOGY

At least three factors could determine the final design. [Figure 1.2](#) shows the relationship between the final design with technology, topology, and methodology. One can foresee the “novelty” of the final design by knowing the level of the “maturity” of these three factors. To “commercialize” an integrated circuit as a product, the level of maturity should be high. The lack of maturity can be considered as research gaps for the researchers. One needs to consider the design for test (DFT) or design for manufacturability (DFM) for the final design.

Normally, standard Complementary Metal-Oxide Semiconductor (CMOS) technology is only targeted for the digital circuit. The technology does not have multiple

FIGURE 1.2 Design dimension.

polysilicon, and there are no dedicated passive components such as MIM capacitor, high sheet resistance resistor, and inductor. However, many analog circuits have used standard CMOS technology.

There are also mixed-signal and RF CMOS technology, which are targeted for the mixed-signal and RF application. The thick metal, which is for inductor design has been included for the RF CMOS technology. The advanced CMOS technology such as for Radio Frequency (RF) application is expensive compared to standard CMOS technology.

1.4 ANALOG AND MIXED-SIGNAL INTEGRATED DESIGN CONCEPTS

Analog and digital circuits combined in an Integrated Circuit (IC) are considered mixed-signal designs.

Leakage power and propagation delay are the two major challenges in designing digital CMOS Very Large-Scale Integration (VLSI) circuits, in deep sub-micron technology. While for the analog CMOS, voltage swing, noise, and frequency performance are three main challenges. Understanding device behavior is very important, for example, minimum gate length would give the highest speed, thus reducing the propagation delay. While for analog CMOS, the gate length of at least twice the minimum gate length would give the best trade-off of noise, gain, and speed. A trade-off idea is shown in Figure 1.3. Therefore, for the mixed-signal integrated circuits, different gate lengths are utilized for the best performance. Figure 1.4 shows how we can arrange the analog and digital circuits in an IC. Signal integrity and EMI have to be seriously considered for high frequency application.

FIGURE 1.3 Trade-off.

FIGURE 1.4 Block diagram layout of a pipeline stage.

1.5 SUMMARY

This book focuses on the custom analog and mixed-signal integrated circuits. This book will not focus on the basic digital circuit design, digital coding-related, and back-end digital layout tool. Knowledge of the technology or process that is used in circuit design is very crucial. Good design requires solid knowledge in the process or technology. This is reflected in [Figure 1.2](#). Chapter 2 details only standard CMOS because the technology is still practical in the coming years. The rest of the chapters’ design concept is still applicable for different technologies. This book stresses many figures and curves to describe the operation and behavior of circuitries. Readers are encouraged to scrutinize the figures and curves for a better understanding of any given subjects.

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