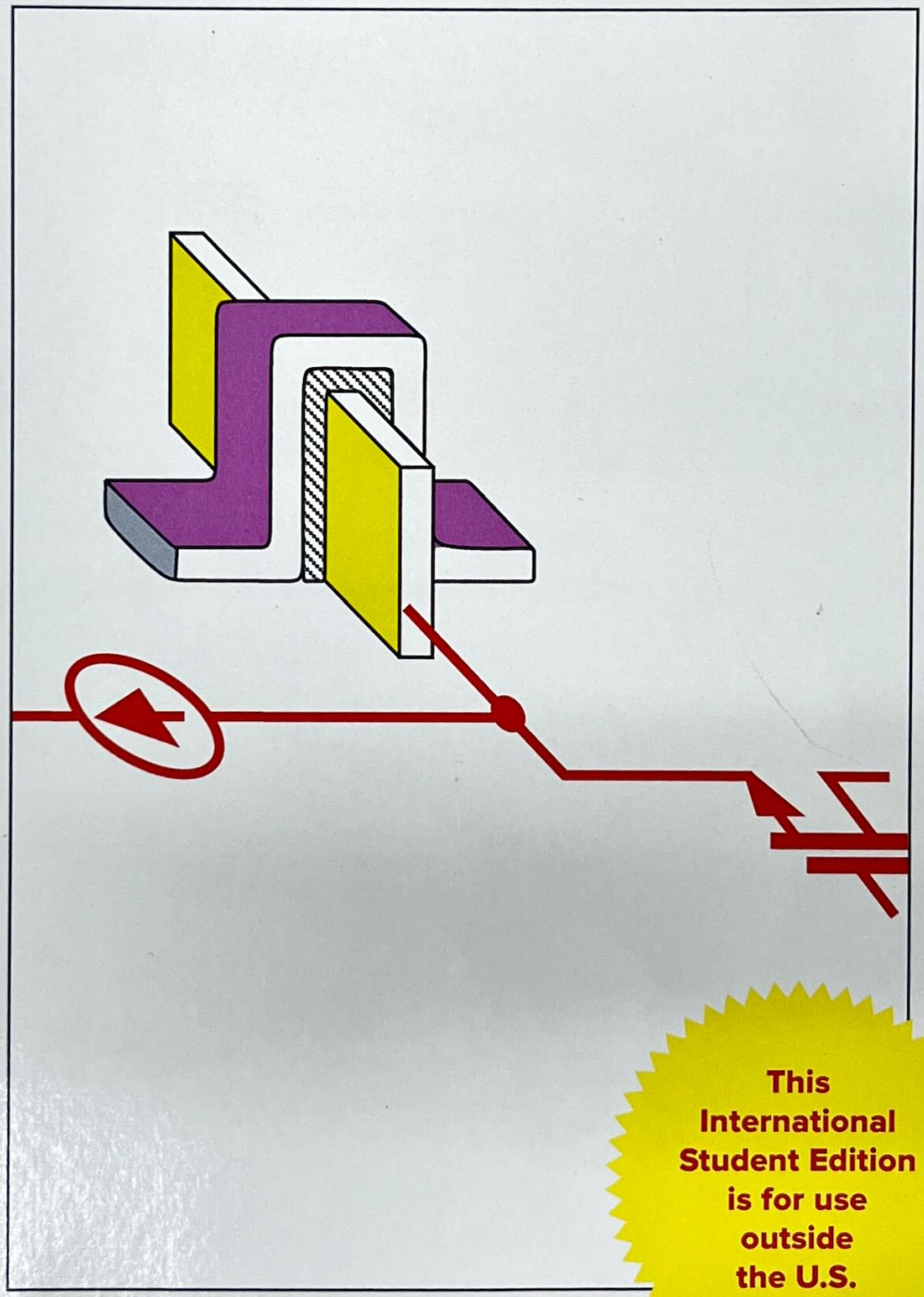
Behzad Razavi

Design of Analog CMOS Integrated Circuits

Second Edition



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McGRAW-HILL EDUCATION INTERNATIONAL EDITION

Design of Analog CMOS Integrated Circuits

Second Edition

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Mc Graw Hill Education

Preface to the Second Edition

When I submitted proposals to publishers for the first edition of this book, they posed two questions to me: (1) What is the future demand for analog books in a digital world? and (2) Is it wise to publish a book dealing solely with CMOS? The words "analog" and "CMOS" in the book's title were both in question.

Fortunately, the book resonated with students, instructors, and engineers. It has been adopted by hundreds of universities around the world, translated to five languages, and cited 6,500 times.

While many fundamentals of analog design have not changed since the first edition was introduced, several factors have called for a second: migration of CMOS technologies to finer geometries and lower supply voltages, new approaches to analysis and design, and the need for more detailed treatments of some topics. This edition provides:

- Greater emphasis on modern CMOS technology, culminating in a new chapter, Chapter 11, on design methodologies and step-by-step op amp design in nanometer processes
- Extensive study of feedback through the approaches by Bode and Middlebrook
- A new section on the analysis of stability using Nyquist's approach—as the oft-used Bode method falls short in some common systems
- Study of FinFETs
- Sidebars highlighting important points in nanometer design
- A new section on biasing techniques
- Study of low-voltage bandgap circuits
- More than 100 new examples

Some instructors ask why we begin with square-law devices. This is for two reasons: (1) such a path serves as an intuitive entry point and provides considerable value in the analysis of amplifiers in terms of allowable voltage swings, and (2) despite their very short channel lengths, FinFETs—the devices used in 16-nm nodes and below—exhibit nearly square-law characteristics.

This book is accompanied with a solutions manual and a new set of PowerPoint slides, available at www.mhhe.com/razavi.

Behzad Razavi
July 2015

Preface to the First Edition

In the past two decades, CMOS technology has rapidly embraced the field of analog integrated circuits, providing low-cost, high-performance solutions and rising to dominate the market. While silicon bipolar and III-V devices still find niche applications, only CMOS processes have emerged as a viable choice for the integration of today's complex mixed-signal systems. With channel lengths projected to scale down to 0.05 μm, CMOS technology will continue to serve circuit design for another two decades.

Analog circuit design itself has evolved with the technology as well. High-voltage, high-power analog circuits containing a few tens of transistors and processing small, continuous-time signals have gradually been replaced by low-voltage, low-power systems comprising thousands of devices and processing large, mostly discrete-time signals. For example, many analog techniques used only ten years ago have been abandoned because they do not lend themselves to low-voltage operation.

This book deals with the analysis and design of analog CMOS integrated circuits, emphasizing fundamentals as well as new paradigms that students and practicing engineers need to master in today's industry. Since analog design requires both intuition and rigor, each concept is first introduced from an intuitive perspective and subsequently treated by careful analysis. The objective is to develop both a solid foundation and methods of analyzing circuits by inspection so that the reader learns what approximations can be made in which circuits and how much error to expect in each approximation. This approach also enables the reader to apply the concepts to bipolar circuits with little additional effort.

I have taught most of the material in this book both at UCLA and in industry, polishing the order, the format, and the content with every offering. As the reader will see throughout the book, I follow four "golden rules" in writing (and teaching): (1) I explain *why* the reader needs to know the concept that is to be studied; (2) I put myself in the reader's position and predict the questions that he/she may have while reading the material for the first time; (3) With Rule 2 in mind, I pretend to know only as much as the (first-time) reader and try to "grow" with him/her, thereby experiencing the same thought process; (4) I begin with the "core" concept in a simple (even imprecise) language and gradually add necessary modifications to arrive at the final (precise) idea. The last rule is particularly important in teaching circuits because it allows the reader to observe the evolution of a topology and hence learn both analysis and synthesis.

The text comprises 16 chapters whose contents and order are carefully chosen to provide a natural flow for both self-study and classroom adoption in quarter or semester systems. Unlike some other books on analog design, we cover only a *bare minimum* of MOS device physics at the beginning, leaving more advanced properties and fabrication details for later chapters. To an expert, the elementary device physics treatment my appear oversimplified, but my experience suggests that (a) first-time readers simply do not absorb the high-order device effects and fabrication technology before they study circuits because they do not see the relevance; (b) if properly presented, even the simple treatment proves adequate for a substantial coverage of basic circuits; (c) readers learn advanced device phenomena and processing steps much more readily *after* they have been exposed to a significant amount of circuit analysis and design.

Chapter 1 provides the reader with motivation for learning the material in this book. Chapter 2 describes basic physics and operation of MOS devices.

Chapters 3 through 5 deal with single-stage and differential amplifiers and current mirrors, respectively, developing efficient analytical tools for quantifying the behavior of basic circuits by inspection.

Chapters 6 and 7 introduce two imperfections of circuits, namely, frequency response and noise. Noise is treated at an early stage so that it "sinks in" as the reader accounts for its effects in subsequent circuit developments.

Chapters 8 through 10 describe feedback, operational amplifiers, and stability in feedback systems, respectively. With the useful properties of feedback analyzed, the reader is motivated to design high-performance, stable op amps and understand the trade-offs between speed, precision, and power dissipation.

Chapters 11 through 13 deal with more advanced topics: bandgap references, elementary switched-capacitor circuits, and the effect of nonlinearity and mismatch. These three subjects are included here because they prove essential in most analog and mixed-signal systems today.

Chapter 14 is concerned with high-order MOS device effects and models, emphasizing the circuit design implications. If preferred, the chapter can directly follow Chapter 2 as well. Chapter 15 describes CMOS fabrication technology with a brief overview of layout design rules.

Chapter 16 presents the layout and packaging of analog and mixed-signal circuits. Many practical issues that directly impact the performance of the circuit are described and various techniques are introduced.

The reader is assumed to have a basic knowledge of electronic circuits and devices, e.g., *pn* junctions, the concept of small-signal operation, equivalent circuits, and simple biasing. For a senior-level elective course, Chapters 1 through 8 can be covered in a quarter and Chapters 1 through 10 in a semester. For a first-year graduate course, Chapters 1 through 11 plus one of Chapters 12, 13, or 14 can be taught in one quarter, and almost the entire book in one semester.

The problem sets at the end of each chapter are designed to extend the reader's understanding of the material and complement it with additional practical considerations. A solutions manual will be available for instructors.

Behzad Razavi
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Acknowledgments for the Second Edition

The second edition was enthusiastically and meticulously reviewed by a large number of individuals in academia and industry. It is my pleasure to acknowldege their contributions:

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Finally, I wish to thank my wife, Angelina, for her continual help with typing and organizing the chapters.

Acknowledgments for the First Edition

Writing a book begins with a great deal of excitement. However, after two years of relentless writing, drawing, and revising, when the book exceeds 700 pages and it is almost impossible to make the equations and subscripts and superscripts in the last chapter consisent with those in the first, the author begins to feel streaks of insanity, realizing that the book will never finish without the support of many other people.

This book has benefited from the contributions of many individuals. A number of UCLA students read the first draft and the preview edition sentence by sentence. In particular, Alireza Zolfaghari, Ellie Cijvat, and Hamid Rafati meticulously read the book and found several hundred errors (some quite subtle). Also, Emad Hegazi, Dawei Guo, Alireza Razzaghi, Jafar Savoj, and Jing Tian made helpful suggestions regarding many chapters. I thank all.

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My wife, Angelina, has made many contributions to this book, from typing chapters to finding numerous errors and raising questions that made me reexamine my own understanding. I am very grateful to her.

The timely production of the book was made possible by the hard work of the staff at McGraw-Hill, particularly Catherine Fields, Michelle Flomenhoft, Heather Burbridge, Denise Santor-Mitzit, and Jim Labeots. I thank all.

I learned analog design from two masters: Mehrdad Sharif-Bakhtiar (Sharif University of Technology) and Bruce Wooley (Stanford University), and it is only appropriate that I express my gratitude to them here. What I inherited from them will be inherited by many generations of students.

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