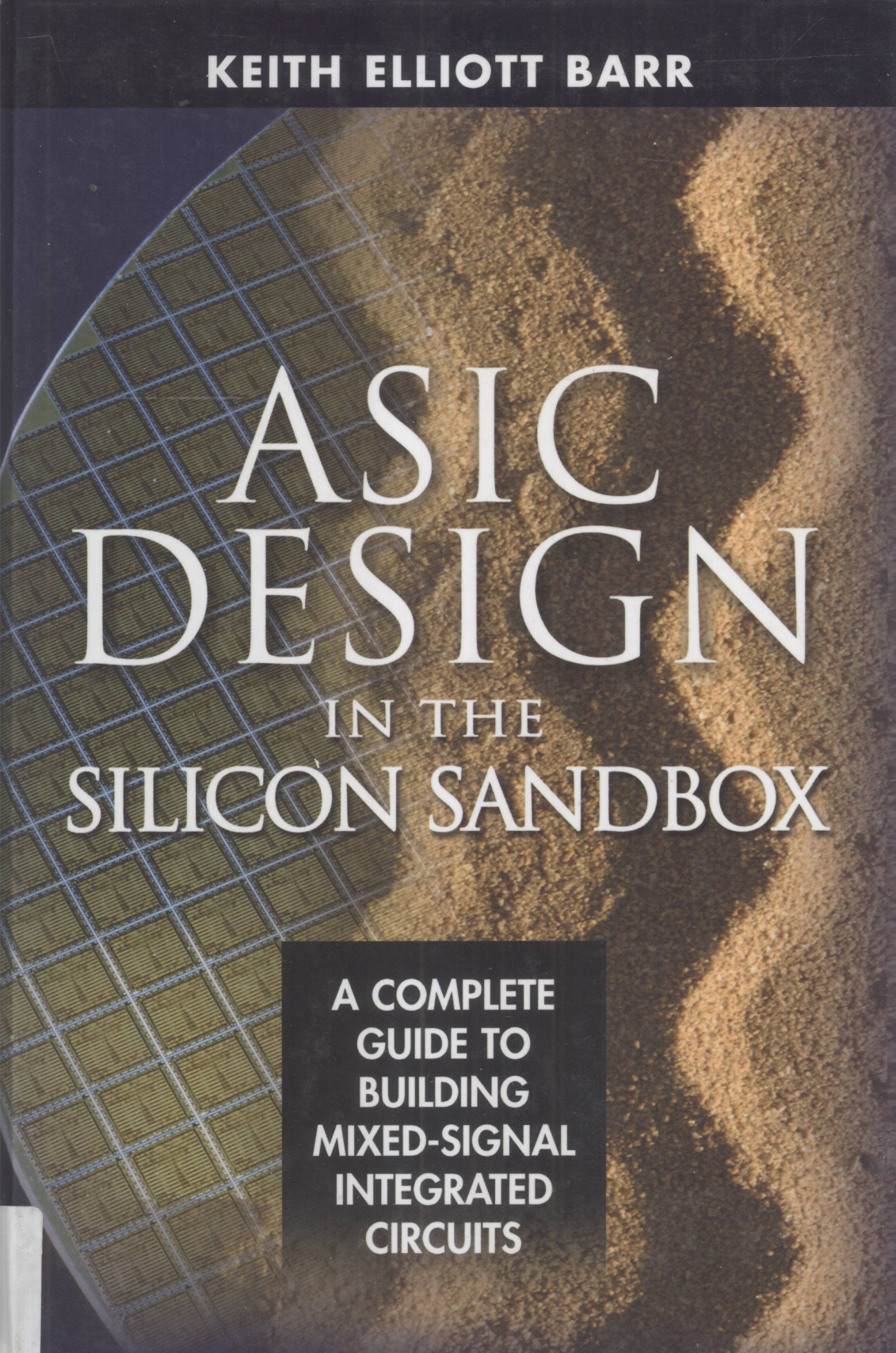
KEITH ELLIOTT BARR



ASIC DESIGN IN THE SILICON SANDBOX

A COMPLETE GUIDE TO BUILDING MIXED-SIGNAL INTEGRATED CIRCUITS

ASIC Design in the Silicon Sandbox

A Complete Guide to Building Mixed-Signal Integrated Circuits

Keith Barr

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ABOUT THE AUTHOR

Keith Barr designed his first salable electronic product at the age of 12—a biomedical device for his physician-uncle's practice. Largely self-educated, he founded MXR Innovations, based in Rochester, NY, and later, Los Angeles-based Alesis Studio Electronics; each of which grew to dominate the music industry in analog and digital audio effects, synthesis, and other technologies. One of Keith's developments, the Alesis ADAT recorder, became the audio industry standard for digital multitrack recording. In between audio companies, he took a few years off to roam the Caribbean in a sailboat and later to design and market a radiation detector for lab and field use.

Held back in the ninth grade for failing a history course, he proceeded to take all of the school's available science courses and left on his sixteenth birthday. He would later work as a technician and then as an engineer, starting his own company when he turned 21. His unusual beginnings provide him a unique perspective toward technology and the way science is taught.

Keith has authored a number of design and technical patents. Of his current companies, Exelys creates products in the fields of medical and sports technology, while Spin Semiconductor develops ASICs for OEM sales. He is now interested in the organic synthesis of fragrances and flavors. Keith resides with his wife and two children at homes in Los Angeles and Taipei.

Dedicated to all of those who see life as a continuous learning experience.

Foreword

Designing chips is fun. There are many reasons to design a custom integrated circuit, including lower cost, higher performance, higher reliability, lower power, smaller size, and protection from reverse engineering. To these reasons, Keith Barr emphatically adds another one—enjoyment for the designer. While outside this book it is seldom discussed in print, electronic designers understand this joy. Tackling the trade-offs while building up the desired functionality of an electronic system from lower level components is like solving a puzzle. Except with electronics, after solving the puzzle, you can hold the newly created object in your hand, you can see it functioning and, hopefully, you can see it take hold in the marketplace, due in large part to the electronics design solution that you have crafted. Call it satisfaction or call it fun, it's the essence of the electronic design experience.

In this book, Keith Barr demystifies the integrated design process. He assumes that you are already an electronics engineer, but at the printed circuit board level. In chapter after chapter, he adds the information you need to know to not just design using someone else's chip but to design your own chip. This book contains the distillation of half-a-dozen textbooks, dozens of published papers, and years of experience down into just what you need to know to design a chip. The discussion on economics in Chapter 3 is unlike any published work I have seen and should be a must-read for anyone involved in integrated circuit design, whether novice or experienced pro.

As engineers gain experience, they generally are worth more. As your bag of tricks expands, so does your salary. And being able to design the inside of an integrated circuit is one neat trick. So read this book cover to cover and then go and design your first integrated circuit. It will

likely lead to greater financial rewards, but also to a lifelong passion for the art and craft of custom integrated circuit design. Jump into the silicon sandbox and have fun!

John Tanner, Ph.D.
Founder and CEO
Tanner Research, Inc.

Introduction

I absolutely love to design electronic hardware. It is the most interesting challenge, rich with choices and trade-offs; a solvable puzzle that verges on art. When trying to find a circuit solution it's difficult to resist delving deeper into the system within which the target circuit lives. In electronics, no circuit exists in isolation; systems are a holistic continuum of signals, noises, power, production issues, cost, and so forth. In attempting to solve a circuit puzzle, you often end up redesigning the entire system.

I began my electronics career at a very young age, building projects with vacuum tubes. At the age of 12, I had my first germanium transistors to build simple battery-powered circuits, and at 14, cheap silicon devices in plastic packages opened up a whole new world of possibilities. When op-amps became available, things got really interesting; then the microcomputer and the EPROM caused the sky to open up. Now we can put almost everything on a single chip of silicon, and conjure up parts to our liking by simply drawing shapes on a computer screen... resistors, capacitors, transistors of any size and shape... each in itself so cheap, they're virtually free. For any designer that loves a challenge and sees his work as art merged with science, THIS is the place to be.

I began my IC design journey by asking questions of a consultant I had hired to do an IC design detail, and got hooked in the process. I was astounded by how simple the fundamentals were, but then often felt overwhelmed by the details. The consultant's results weren't very successful, but I went on with his teachings to finish the project with a small team of engineers that had no previous experience with IC design. One very successful product ended up with half-a-dozen custom circuits—everything from wideband, low-noise preamps to error correction logic circuits and servo motor controllers.

From personal experience I know that many inspired engineers are stuck in the world of standard components interconnected on circuit boards. They have the ability to write code, program FPGAs, lay out PCBs, design logic circuits and analog filters, and conquer complex RFI issues, but never were properly exposed to the option of actually designing their own ASIC. This book is an introduction for that engineer. My desire is to reveal both the simplicity and the complexity of ASIC design to engineers who have no prior knowledge of the field, with practical advice that will hopefully encourage them to take the next logical step in the evolution of electronics engineering.

Books exist on the design of circuits, so I will only refer to circuits that I have found practical and especially useful; this is not a tutorial on electronics engineering. Books and papers exist for the experienced IC designer, to whom this book is intended only as an introduction. Throughout, my intent is to be as practical as possible, involving not only the technical aspects but financial ones too, as the cost of ASIC design is by no means insignificant; another objective is to show that the expense is often trivial compared to the advantages gained.

Whether you're an engineer working for a small company or a pioneer who aims to start up a new venture, this book will hopefully show you the path to a new way of seeing your craft. This is the trick: If you understand electronics and can design at the PCB level, the skills required for full ASIC design are already in your possession. Most engineers see ASIC design as some foreign, high-level specialty, and I argue that it is most emphatically NOT. Yes, you need to learn the ins and outs of a few new computer tools, and yes, there are limits and quirky problems, but they are easily learned. Once you have finished this book, you should be well on your way.

Possibly the most satisfying aspect of ASIC design is that, within the boundaries of the process you have selected, you are in complete control. There is no end to the number of ways a system-on-a-chip can be structured, and the result becomes a unique expression of the designer.

I have taken every opportunity to make this introductory book as comprehensive as possible, overturning rocks that most writers would leave alone. The result is somewhat scattered, attempting to collect interconnected elements from a multidimensional universe of ideas into a grouped series of linear thoughts. Please accept my apology for jumping from one subject to another, or pausing occasionally to delve deeper into an area I feel is important.

I have made every attempt to remove equations from the book, relying on simple described relationships for understanding. The powerful capability of the SPICE analysis program makes knowledge of the equations behind IC process development unnecessary. If you intend to develop your own IC process, this is not the book for you. If you want to

use an IC process, then you don't need to know the underlying equations, because you can't change the process you're working with. SPICE has simplified the management of the calculations, in much the same way as the pocket calculator made manual long division obsolete. I will continually emphasize the *behavior* of a device as being more important than the way it *works*. I fully appreciate any curiosity you may have about the way it works, but for IC design only behavior matters, and SPICE reveals behavior readily.

One final note on the tone of this book: Some subjects are detailed, and you will need to "slog" through, hopefully getting to the end without losing your focus. I surely hope the tone is not pedantic to your ear. I ended my formal education at the age of 16, having been held back two full years in high school, and left to enter the real world where I could begin my education at the earliest opportunity. I am not a professor, and I'm sorry if I sometimes sound like one. I want your experience with this book to be enlightening and fun. Further, it should be inspiring to know that formal education is not a prerequisite for custom circuit design.

It is my hope that, provided the reader has a good grounding in electronics engineering, this will be the only book he will ever need, outside of tool manuals and process specification documents, to begin advanced work immediately. Any additional texts would be very specific and quite advanced.

The subtitle of this book is "A Complete Guide to Building Mixed Signal Integrated Circuits," but for me, it is "The joy of IC design." My sincere hope is that you find the subject just as fascinating, and will make the effort to come play in the silicon sandbox.

Keith Barr

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Chapter

1

The Sandbox

Analog and digital circuits combined in an IC are considered *mixed-signal* designs. Integrating the two types of circuitry can be challenging, but these designs can provide *system-on-a-chip* (SOC) functionality that, once designed into a product, can significantly impact final product cost. As a designer of commercially viable products, already buying ICs from major suppliers, you could approach a major IC company and suggest that they design a new catalog part for your application; but without some costly agreement, they would likely offer the part to your competitors as well, somewhat dulling the advantage you may be seeking. You can contract an IC design house to produce a design for you, but in the process you will be transferring specific knowledge of your business to others that you may not be able to completely control. Communication of exactly what you need is difficult without knowledge of the IC design process; it's like a sales guy talking to an engineer, enough said? Further, the cost of having a design house do the work can easily approach a million dollars, even for a fairly simple design. If you do your own design, you can keep the details as the intellectual property of your company and get exactly what you want, at lower cost, with well-known reasons for any trade-offs.

IC Overview

Integrated circuits are fabricated onto *silicon wafers*, subsequently diced or sawn into individual *die* and *lead bonded* onto a *leadframe*, and then packaged with a surrounding mineral-filled thermosetting packaging material, or in the case of a *ceramic package*, a lid is attached. Depending on die size and wafer diameter, as few as 10 or as many as 50,000 devices could result from a single wafer. Every IC you currently purchase and