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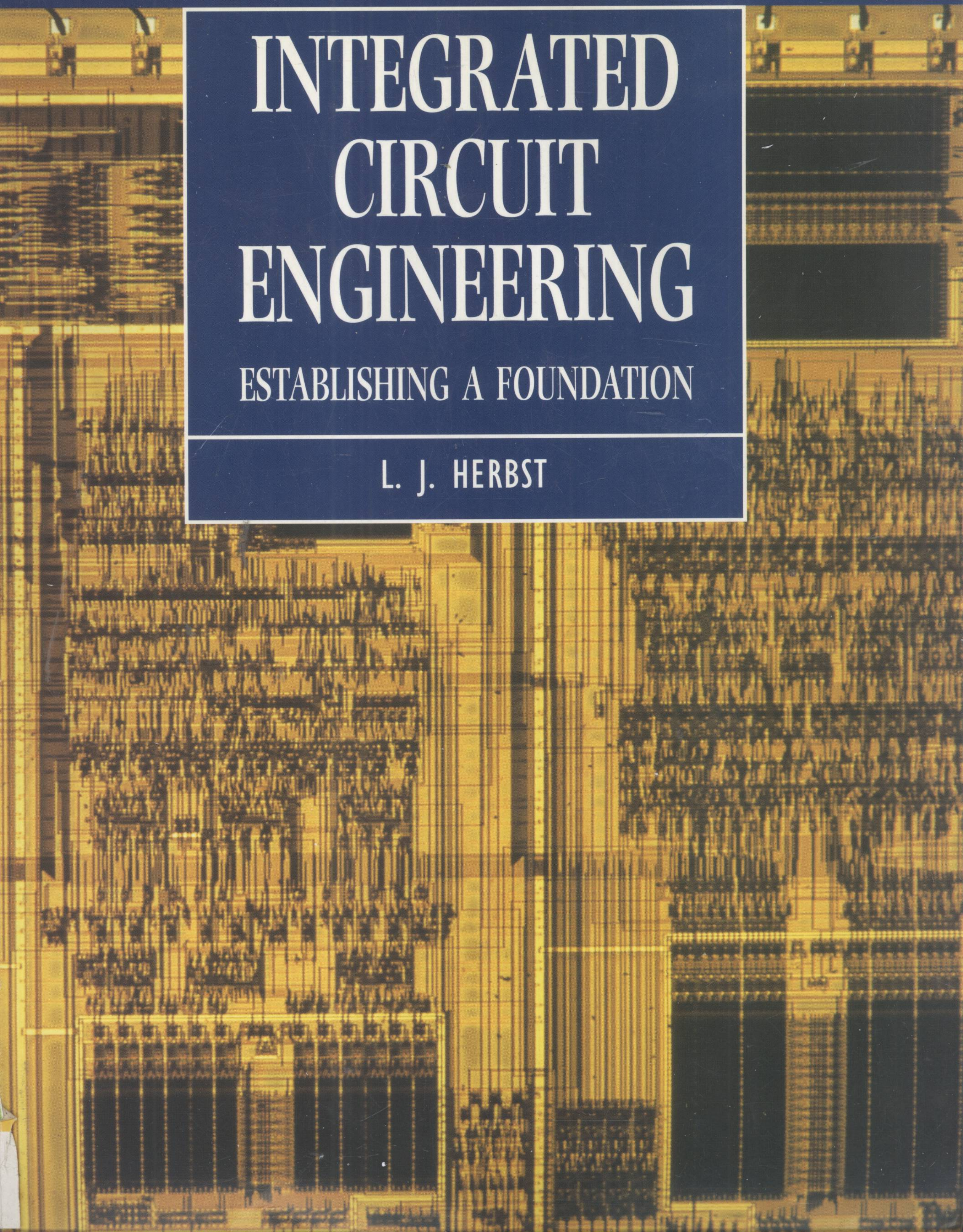
INTEGRATED CIRCUIT ENGINEERING

ESTABLISHING A FOUNDATION

L. J. HERBST



Integrated Circuit Engineering

Establishing a Foundation

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To my wife

Preface

Integrated circuits (ICs) occupy a key role in electronics and are to be found in almost every conceivable product of consumer, industrial, and military electronics. They are routinely included in the curriculum of first degrees in electrical/electronic engineering. Many other first degrees in related disciplines like microelectronics and computer engineering also contain substantial material on ICs. The evolution of very-large-scale integration (VLSI) has radically altered the nature of IC engineering. The electronic circuits of a complex system like a computer can now be contained in one or a small number of chips. The nature of VLSI is being brought home to engineers in the form of application-specific ICs (ASICs), which involve customers in their design.

Based on my personal experience of teaching ICs and VLSI on first degrees and on special courses (which I organized) in industry, I perceived the need for a comprehensive text on IC engineering which recognizes the centrality of VLSI, but also embraces lower levels of integration. There is at present a serious gap in such literature. Nothing has been published since 1977 to compare with the comprehensive texts on IC engineering by Hamilton and Howard (1975) and Glaser and Subak-Sharpe (1977). The many books on ICs which have appeared during the last twenty years are generally pitched at a graduate rather than an undergraduate level and tend to be specialized, covering subjects like MOS ICs, VLSI, and IC technology.

This book gives a broad, comprehensive coverage of ICs, embracing fabrication, circuit techniques, and VLSI/ASIC system aspects. Technology is likewise covered in breadth by including bipolar, MOS, and GaAs ICs. It is assumed that readers will have a background in basic transistor operation, analogue and digital circuit practice, and digital design. Alternatively undergraduates may be taught these subjects in parallel with the contents of this book, which is aimed at the second and third years of a British, and the second, third and fourth years of an American degree. The text also meets a vital need for continuing education. Much of the subject matter it contains will probably be new to most engineers and scientists who have graduated some years ago. For that reason this book should prove to be very attractive for career–long learning.

Coming to the details of the contents, the text begins with a general survey (Chapter 1). Device fabrication and packaging (Chapter 2) come next. Chapter 3 covers the formation of transistors, resistors and capacitors, and Chapter 4 outlines device behaviour and modelling. Circuit techniques form the subjects of Chapter 5 (digital) and Chapter 6 (analogue). The last few years have seen a distinct swing towards more analogue and mixed-mode (analogue and digital) ICs, brought about largely by the growth in telecommunications. That situation is reflected in the contents of Chapter 6, the largest chapter in the book, and the inclusion of mixed-mode ASICs in Chapter 10. Chapter 7 on semiconductor memories initiates the VLSI/ASIC sector, which extends to the end of the book. An overview of ASIC design styles in Chapter 8 paves the way for a fuller treatment of ASICs in Chapters 9 to 11. Chapter 9 describes programmable logic devices (PLDs) with a strong emphasis on field programmable gate arrays (FPGAs). Chapter 10 deals with the characteristics and design issues of ASICs, including economics and design for testability, and Chapter 11 covers ASIC design techniques. Finally Chapter 12 looks at submicron scaling and projections of ICs for the immediate future. Electronics abounds with acronyms and jargon, which are defined in a glossary at the end of the text for ease of reference.

The style of presentation departs in a number of ways from the orthodoxy found in the majority of books on ICs. My first and foremost consideration has been to highlight the engineering dimension. Many publications within the last two decades on the teaching of engineering have urged the need for more material on engineering practice and design, and less on analysis (ASEE 1987; Finniston 1980). Inspite of this there is a continuing trend towards a concentration on analysis.

The roles of analysis and synthesis in this book embody some ideas which I advanced at two conferences in the US (Herbst 1987 and 1989). Analysis has been greatly reduced relative to the traditional presentation in many established texts on ICs. Second synthesis has been carefully structured to illustrate current engineering practice. Last synthesis is often placed before analysis, frequently in the form of an overview at the beginning of a chapter. My approach bears some resemblance to the inverted curriculum proposed by Cohen (1987 and 1992). Extensive quotations of IC specifications and performance bring home the capabilities of current ICs, and this information is continually interwoven with the rest of the text, sometimes even within the analytical sections. The profuse quotations of current IC performance are open to the charge that such material will soon become dated. There is a characteristic American saying that if a piece of equipment works it is out of date. However the probable changes in the performance of future ICs, mainly due to continuing miniaturization, are dealt with, and readers should be able to appreciate the capabilities of new products emerging within the next few years without undue difficulty (Mead and Conway 1980).

The accent on engineering design and applications in this text is long overdue. Much of the engineering science and mathematics of an engineering undergraduate curriculum is unnecessary and can be eliminated, making way for material on synthesis, design and applications (Finniston 1980, pp.94–5). Nevertheless a balance must be maintained between analysis and synthesis: the danger of overemphasizing the engineering aspects to the detriment of fundamental concepts is very real.

Muller and Kamins (1986) hold successful engineering to rest on two foundations, physical concepts and technology. Zorpette (1984) warns against excessive emphasis on what he calls the technology of the moment. Everitt (1980) defined the fundamental difference between science and engineering to be the difference between analysis and synthesis, and went on to say that synthesis can only be accomplished after a thorough grounding in analysis. G.M. Trevelyan (1946), the late great English historian, was right when he told us that 'disinterested intellectual curiosity is the life-blood of real civilization'. However hard-pressed engineers may be in industry, where they are often pushed from pillar to post in order to come up with designs for new equipment or to meet critical production schedules, they must preserve an element of detached intellectual curiosity for part of their work. In the light of these comments I have taken care to stress fundamental concepts and to avoid preoccupation with engineering immediacy.

It remains for me to express my gratitude for the help I have received from various sources. Apart from obtaining databooks from semiconductor vendors, I had countless conversations with staff from these establishments to clear up matters on which I felt uncertain, or to obtain additional information. This help was given most willingly without exception and has been of tremendous value. The manuscript has been produced and typeset with the aid of computer typesetting software by Trevor and Rose Atkinson, who have very effectively accommodated special requirements regarding style and have been most helpful throughout. I am indebted to Colin Gregg, who has drawn all the diagrams with the aid of computer graphics, and has in many cases improved on the originals submitted to him. The help and cooperation of the publishers at all stages of the production is gratefully acknowledged.

Last and most I am indebted to my wife for her unstinting support for this undertaking, which made a severe inroad on the time for normal domesticity. It is only her encouragement and understanding which have made this book possible.

Middlesbrough L.J.H.
September 1995

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On a more general note, the author advises that the quotations of data from the establishments listed are only guidelines, but that fuller information, sometimes going beyond what is available in databooks and datasheets, should be consulted for actual designs.

Contents

1

Overview

1.1 IC structure

The nature of electronic equipment based on integrated circuits (ICs) is illustrated in Fig. 1.1, the photograph of a motherboard, a printed circuit board (PCB) for a personal computer (PC). The motherboard is the core of the electronics for the computer. It contains numerous ICs of various types and sizes, in addition to a few *discrete* components (resistors, capacitors, crystal oscillators), and sockets for interconnecting the motherboard to other PCBs. The ICs have transistor counts ranging from about 100 to 250 000 per package, and are interconnected to form a highly sophisticated system. The complexity of an IC in this era of very-large-scale integration (VLSI) is evident from the photograph in Fig. 1.2, which shows the surface of a *die* (signifying an unencapsulated chip). That die contains over 100 000 transistors, has 68 bonding pads, and measures about $8 \times 8\ \text{mm}^2$. It is encapsulated in a 68-pin square package not much larger than the die. This section presents a very brief outline of the structure and the processing leading to an IC.

Figure 1.3 shows the profile of a die. The electrodes of all active (transistors and diodes) and passive (resistors and capacitors) components are

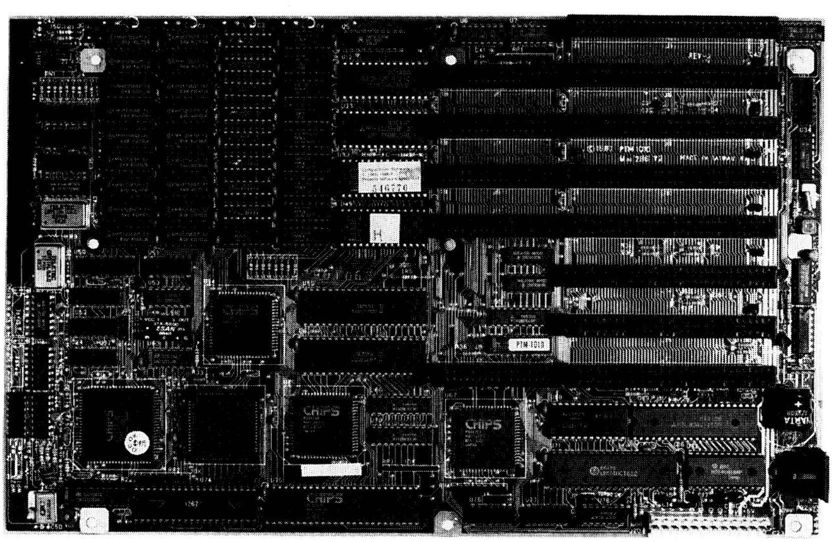

Fig. 1.1 PC motherboard photograph (Courtesy of Opus Technology)