Monolithic Integrated Circuits

Techniques and Capabilities

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CLARENDON PRESS • OXFORD 1985

Oxford University Press, Walton Street, Oxford OX2 6DP
Oxford New York Toronto
Delhi Bombay Calcutta Madras Karachi
Kuala Lumpur Singapore Hong Kong Tokyo
Nairobi Dar es Salaam Cape Town
Melbourne Auckland
and associated companies in
Beirut Berlin Ibadan Mexico City Nicosia

Oxford is a trade mark of Oxford University Press

Published in the United States
by Oxford University Press, New York

British Library Cataloguing in Publication Data

Herbst, L. J.
Monolithic integrated circuits: techniques and capabilities.
1. Integrated circuits
I. Title
621.381'73 TK7874

ISBN 0-19-859329-5

Library of Congress Cataloging in Publication Data

Herbst, L. J.
Monolithic integrated circuits.

Bibliography: p.
Includes index.
1. Integrated circuits. I. Title.
TK7874.H42 1985 621.381'73 84-20788
ISBN 0-19-859329-5

Typeset and printed in Northern Ireland by
The Universities Press (Belfast) Ltd

Preface

Integrated circuits present one of the most fascinating and important technologies of this age. They pervade every aspect of current technological endeavour, and play a decisive part in information technology. Almost every aspect of engineering, and indeed of our way of life, is being changed by the impact of microelectronics.

The integrated circuit (IC) has inevitably had the most immediate and radical effect on electronic engineering, which has expanded in many new directions following the invention of the transistor, the developments of the first integrated circuits in the early 1960s, and the emergence of the microcomputer in the early 1970s. Integrated circuits are now found in virtually all electronic equipment, with applications extending from consumer electronics, for example integrated circuits for quartz wrist watches and washing machines, to large computer systems. The arrival of the microprocessor-based microcomputer ushered in the era of very-large-scale integration (VLSI), which is having a most profound effect on the nature and applications of integrated circuits. Whereas integration up to then consisted largely of elements containing one or several identical circuits, VLSI has moved the technology towards the integration of an entire system like a microprocessor, or even a microcomputer, on a single chip. In doing so, VLSI has brought a new design philosophy to IC engineering and practice, building on the basic foundation of IC technology established prior to its arrival but extending well beyond it and demanding a fresh approach geared towards the design of an electronic system on a single chip. One result of VLSI is that digital circuits and techniques have further strengthened their already commanding position.

All these recent developments are reflected in this book, which combines the fundamentals of IC technology, circuit design principles, and IC application capabilities. There is already a substantial number of texts on semiconductor device physics, which is explained with an emphasis on ICs and their applications. However, there appears to be a lack of texts which concentrate on the techniques and capabilities of ICs. This book seeks to fill that gap and has the prime aim of imparting a sufficiently detailed understanding of ICs for the reader to be able to use them to the best advantage. In order to do so, a qualitative appreciation of the various fabrication processes will be needed as well as an understanding of the basic circuit techniques from which to proceed to the actual use of the IC chips themselves.

The text is aimed at a wide readership. Generally many qualified electrical and electronic engineers will need to supplement their knowledge of ICs gained during their years of formal study. This applies especially to the graduates of yesteryear, whose curriculum may well not have included ICs at all. However, this book is not aimed solely at those professionally qualified in electrical and electronic engineering. The tremendous increase in digital computing has led to a large number of engineers and computer scientists engaged entirely, or almost entirely, in software engineering. Many of these will need to have a deeper understanding of computer hardware, and of ICs in particular, than is normally provided in their undergraduate courses. This book, supplemented with further reading if necessary, should be specifically helpful to that category of reader who is generally trained in computer science, but who additionally has some understanding of semiconductor electronics.

The choice of the material and its presentation have been determined by the readership for whom the book is intended and by the literature on ICs currently available. The overriding importance of digital electronics is reflected in the weighting given to digital ICs; indeed the analogue section is largely confined to two chapters dealing with operational amplifiers and data converters. The IC user will have considered, in arriving at his choice, not merely the circuit performance but also the various processes and their potential for yielding the best chips for a given application. This consideration has greatly influenced the presentation of the circuit techniques, the explanation of which is continuously linked with the processing technologies in a way which helps the reader to appreciate the relative strengths and weaknesses of the various alternative ICs available.

In order to engender an engineering awareness of what is available, it was decided to give extensive representative outline specifications of current commercial ICs. Naturally this information is in danger of becoming more dated than other material: indeed there is the American saying that if electronic equipment works, it is out of date. However, the information for 'catalogue engineering' presented here should be of direct relevance for five years at least, and possibly longer.

The arrival of VLSI has had a major influence on the way the material of the book has been chosen. The last four chapters are specifically dedicated to VLSI, and include semiconductor memories, microcomputers, and custom/semicustom ICs. The earlier chapters cover the basic IC technologies, logic gates, wired logic (small-scale and medium-scale integration), system aspects of the main digital families, and the analogue circuits already mentioned. The treatment in these earlier chapters is unconventional in that, instead of thinking in terms of wired logic only, the reader is made aware of the role that the various basic circuits play in both wired logic and VLSI, in preparation for the material specific to VLSI which comes later.

To keep the book of reasonable size, some previous knowledge of semiconductor circuit techniques and digital computing principles is assumed. In order to follow this text without having to undertake extensive background studies, readers should preferably have completed one or possibly two years of study on a degree or diploma course. The standard is at undergraduate level throughout, and is suitable for penultimate and final years of an honours degree. However, the treatment is practical enough for much of the book to be within the grasp of senior technicians. Some worked examples have been included in the earlier chapters to illustrate specific aspects of the subject matter, or to complete the material in a helpful way. Those versed in computer science should also have some basic knowledge of semiconductor circuit practice, but they can follow much of the text without it.

Despite the most careful proof-reading, it is inevitable that the book will contain some errors. It is hoped that these will not be serious; the author would be grateful to have them pointed out, and also welcomes suggestions for improvement.

It remains to render thanks to various people and organizations who have helped in the production of the book. First there is the considerable assistance received from Professor W. E. J. Farvis of Edinburgh University, who has acted throughout as the publisher's assessor. His constructive suggestions and critical scrutiny of the text in its various drafts have proved invaluable, and will have enhanced the book in technical merit and style. Thanks are due to Mrs A. L. Harrison for her careful typing of the manuscript. The helpful cooperation and great patience of the publisher is gratefully acknowledged, as is his advice in the preparation of the text and the care taken over its production.

Numerous semiconductor houses and some microcomputer manufacturers, too many to list individually, were only too willing to allow quotations of data relating to their products. In order not to show any particular bias, care has been taken to include a broad cross-section of commercial ICs in these quotations, although second-sourcing is now so universal that, with the exception of a lead in the early stages of a new product, no manufacturer is likely to have a sufficient hegemony to justify laying emphasis on his products over those of others. The choice adopted for the selections has been governed to some extent by information which is readily to hand. Here and there gaps will be found in parameter listings with the comment 'data not available'. Apologies are due to any manufacturer in cases where such data are in fact published. With the large amount of commercial information presented, gaps of this nature will regrettably have occurred.

Finally, I am indebted most of all to my wife for the unfailing support she has given me in this undertaking, which has occupied two and a half

years. The book has been written entirely in my free time. Without her sympathy, understanding, and constant support this would not have been possible.

Middlesbrough L. J. H.
August 1983

Contents

1. Integrated circuits—an overview

1.1. Initial developments

The first integrated circuit (IC) was produced in 1958 for the US Minuteman program. Since then the technology and applications of ICs have dominated electronic engineering. There have been tremendous strides forward and the advances have had a major impact on virtually all applications of electronic circuits. Microelectronics has come to the fore with the microprocessor-based microcomputer and its universal role in industrial and consumer electronics. This chapter outlines the evolution and current state of ICs presenting an overview so that the reader can appreciate how they have reached their present state of development, and how these developments have been fertilized by the potential applications of the progressively advanced IC elements.

The evolution of ICs is characterized by various distinct stages of development. The predominant influence at the beginning of IC production was the US Space Programme. Size and reliability were of particular importance. The limitations of the thermionic valve in digital computers were severely restricting the further development of that application of electronics in its initial stages during the period 1945–1950. It was the invention of the transistor which presented the decisive advance, and allowed the practical realization of systems containing the large number of active components associated with the then already expanding digital computers. Digital electronic circuits became more widespread and universal in the wake of computer development, and offered the prospect of simplifying the circuit construction by utilizing ICs. To be a viable commercial proposition, an IC had to be comparable in cost, and preferably cheaper than, the discrete circuit it displaced. In the economic aspect of assessment, the high initial investment has to be weighed against the striking reduction in unit cost once an item achieves volume production. Figure 1.1 is a general illustration which is also appropriate for new components other than ICs. The high initial cost reflects the large investment needed to launch the product, which is then marketed at a much lower price once volume production is built up. When the IC reaches the stage of obsolescence the price is increased not merely because of reduced production but also to accelerate phase-out, usually in favour of a new and better replacement. An item will be expensive to produce initially, but will be greatly reduced in cost once it progresses, on strength of proven performance, to volume production. The decision to adopt a component at its initial high-cost stage involves taking some

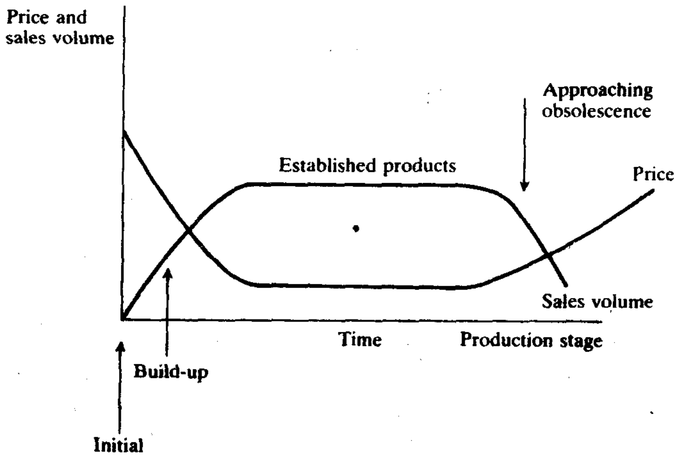

Fig. 1.1. IC price and sales volume.

calculated risks. If a component holds out promise of success, it is pretty safe to reckon with a subsequent substantially reduced cost, making it competitive with the component(s) it replaces on grounds of price alone.

Component cost is, however, not the only consideration. The reliability of electronics is closely linked with the reliability of the interconnections between components and between subsystems, for example printed circuit boards. The reliability of discrete transistors and ICs has progressed to a point where it exceeds the reliability of the aforesaid interconnections. ICs greatly reduce the number of those 'off-chip' interconnections and so will increase system reliability and integrity correspondingly.

So far only component cost has been considered. The system cost is linked to component density. A breakdown will be given below, but evidently the comparison of the costs of discrete and integrated circuits must include the relative efforts of assembly (in particular the wiring and assembly cost). The IC offers the outstanding advantage of reduced wiring, since the connections of the circuit are made within the chip.

The initial assessment given so far highlights three features of ICs which are relevant not only for comparing the use of ICs with discrete components, but also for understanding the nature of the IC developments which have taken place since the introduction of commercial elements in the period 1962–1965. The three major features are as follows:

(i) the cost of the IC compared with the cost of an equivalent circuit constructed with discrete components;

(ii) the system cost comparison between discrete and IC component usage;

(iii) the improvement in system reliability when discrete components are replaced by ICs.

The idea of semiconductor ICs was originally mooted by G. W. A. Dummer of the Royal Radar Establishment (now Royal Radar and Signals Establishment), Malvern, in 1952. Mr. Dummer had the vision to foresee IC development, following the establishment and advance of printed circuit technology in which the substitution of film for screen deposition techniques was already heralding new approaches to interconnections. Although Texas Instruments had produced the first IC in 1958, the real breakthrough which made ICs viable for large-scale use came with the development of the silicon planar transistor by Fairchild in 1959. Silicon planar technology was readily adapted for the formation of ICs in a form well suited to high volume production. The high initial cost of developing a new technology and the high volume of production needed to recover these costs meant that ICs had to be designed from the start for large-volume consumption and had to be standardized.

Data processing offered such a market on the digital side. In analogue microelectronics, the first move was the design of a differential amplifier (Fig. 1.2) which found a major outlet in the operational amplifier configuration shown in Fig. 1.3. However, time has shown that digital circuits are far easier to standardize than analogue circuits, and in terms of market volume digital ICs far outweigh analogue ICs, although this is not to say that the latter are of minor importance.

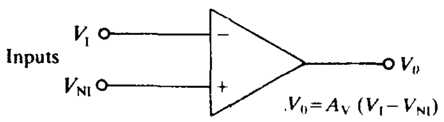

Fig. 1.2. Differential amplifier.

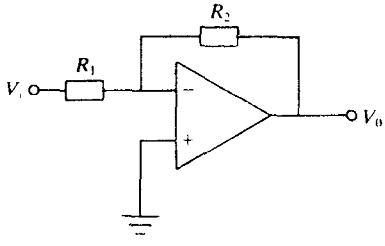

Fig. 1.3. Operational amplifier.

1.2. Advancing from SSI to MSI

Digital ICs became established with the production of the basic logic gates (AND, OR, NAND, NOR, EXCLUSIVE-OR/NOR) and bistables. They were competitive on a strict cost comparison basis, an IC chip being significantly cheaper than its discrete component counterpart. The added advantages already mentioned (increased reliability and reduced system cost) were apparent from the start. Digital logic IC families were at first largely small-scale integration (SSI) chips, followed very soon by medium-scale integration (MSI), later by large-scale integration (LSI), and more recently by very-large-scale integration (VSLI) elements.

Table 1.1 indicates the functional capacities of the various IC categories. SSI was soon followed by MSI (mid 1960s). The late 1960s witnessed the advances leading to LSI; VLSI appeared in the early 1970s.

TABLE 1.1
IC function densities

Category	Approximate number of logic gates per chip
SSI	3–30
MSI	30–300
LSI	300–3000
VLSI	>3000

The motives for increasing the function density per chip are lower system cost and increased reliability. Blakeslee (1979) gives a breakdown of digital system costs which are proportional to the number of ICs used. A condensed version of that analysis is given in Table 1.2. The overhead cost per IC far exceeds the cost of an SSI IC, which is put at \$0.17. Component economics change with time, but the significance of the estimates is that they express a realistic proportion of component to overhead cost. A word of caution is advisable about Table 1.2. The breakdown, in which a contribution towards overhead cost per IC is estimated for various headings, cannot be taken to imply a rigid proportionality between total cost and the number of ICs.

Figure 1.4 is an approximate sketch of system costs in terms of the number of ICs used. The basic unit applies to a minimum system containing one printed circuit (PC) board holding 50 ICs and mounted in a rack which permits system expansion. A quantum jump in cost increase is incurred each time an additional printed circuit board (PCB) is added to the system. If the capacity of 50 ICs (largely SSI) per PCB is adhered

TABLE 1.2

Estimate of digital systems costs proportional to number of ICs (1979 prices)

Item	Cost per Unit	ICs per Unit	Cost per IC ($)
PC board	$20 per board	50 per board	0.40
PC connector	$5 per board	50 per board	0.10
Subrack	$200 per subrack	1000 per subrack	0.20
Backplane	$100 per subrack	1000 per subrack	0.10
Power supplies	$1.50 per watt	10 per watt	0.15
Rack	$500 per rack	4000 per rack	0.13
PC board testing	$5 per board	50 per board	0.10
Testing and assembly	$3580 per rack	4000 per rack	0.89
Service cost (5 years)	$4000 per rack	4000 per rack	1.00
Miscellaneous	$960 per rack	4000 per rack	0.24
Total overhead cost per IC			3.31$

Subrack signifies metalwork, guides and labour.
Rack includes doors, power distributors, etc.
The estimate for power supplies assumes 70 per cent utilization.
(After Blakeslee 1979, by kind permission of John Wiley & Sons Inc.)

to, a system with 60 ICs would demand two PCBs, one of which would be greatly underutilized. However, the estimate in Table 1.2 and the approach adopted are useful for appreciating the influence of economics on IC evolution. Soon after the initial development of digital logic families the advances in technology, yielding greater function density per chip area, led to increasing numbers of MSI ICs becoming available.

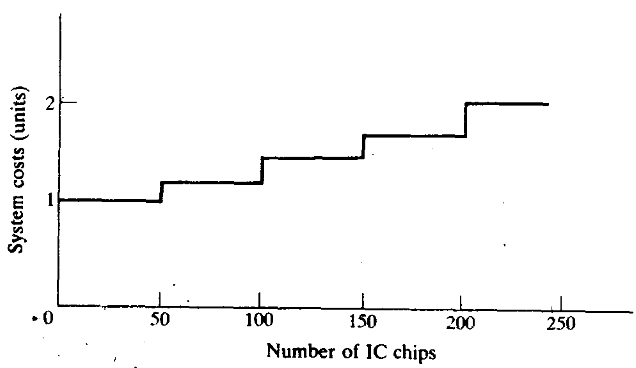

Fig. 1.4. System costs.

The economic advantages of replacing SSI with MSI can be illustrated by a simple example. Let C_{SSI} be the average cost of an SSI IC chip, with a mounting density of 50 such chips per PCB. Suppose now that an MSI IC with a cost C_{MSI} can replace N SSI chips. Let C_0 be the overhead system cost per IC, arrived at in the manner of Table 1.2. The replacement of several SSI ICs by a single MSI IC will be justified on grounds of cost if

$$C_{MSI} + C_0 = N(C_{SSI} + C_0) \tag{1.1}$$

where N is the number of SSI ICs. Equation (1.1) assumes that the same value of system overhead cost per IC applies in both cases. If another parameter $R = C_0/C_{SSI}$ is introduced, eqn (1.1) can be rewritten

$$C_{MSI}/C_{SSI} = N(1+R) - R. \tag{1.2}$$

R comes to about 20 (3.31/0.17). Substituting this value in eqn (1.2) leads to the results shown in Table 1.3. For $N = 2$, an MSI replacement of two SSI chips would be justified even if its cost exceeded that of each SSI chip by a factor of 22! When MSI emerged in significant volume with replacement values N in the range 4–10, the cost of MSI ICs was far below the 'equivalent levels' shown in Table 1.3. MSI was not only far superior to SSI on grounds of component replacement cost alone, but it also increased system reliability and decreased system cost by greatly reducing the number of hard-wired interconnections and test routines.

TABLE 1.3
Cost equivalence—MSI and SSI

N	C_{MSI}/C_{SSI}
2	22
3	42
4	62

When the situation of building a system largely with MSI, with SSI chips decidedly in the minority, is considered, the comparison based on Table 1.2 no longer applies. MSI offers the advantage of greatly reduced overhead and component cost. Everything points to increasing function density per chip in order to improve reliability, reduce system costs (including IC installation and testing), and reduce the component cost of the ICs themselves. By 1968 several digital logic families, which catered for various speeds with the customary speed–power trade-off, had established themselves. The ranges extended from low-power logic capable of operating up to switching rates of around 5 MHz to IC families with a maximum rate of 300 MHz. Great efforts were continually directed towards increasing function density, which amounts to component density per chip, in order to realize the advantages outlined here.

Standardization was, and remains, a cardinal key to the commercial success of ICs. Large-volume production, coupled with technologies that permit higher function densities per IC, made the use of standard components attractive even if these were relatively inefficient. 'Inefficiency' in this context signifies that a particular application could be implemented more elegantly with custom-designed components than with standard IC components. The latter might not be used to the full and several more underutilized standard components might be needed, but the economics of the project point overwhelmingly to the use of standard ICs.

Whilst the component density per IC has been increasing steadily over the years, the actual cost of the IC has remained substantially constant so that the cost per component within the IC has decreased correspondingly. 'Moore's law' postulates that the component and hence the function density per chip double every year (Moore 1975; 1979). Noyce (1977) verified Moore's relationship for the span 1959–1977, and that trend has continued since. With the price cost of the IC itself remaining of the same order throughout this period, the component function cost, reckoned over a period of n years, has decreased by a factor 2^n in that interval. The result is that the cost per component has been reduced by a factor of about a million in the two decades 1959–1979! Not many commodities can boast of such price reduction during that period of high inflation. This reduction has been accompanied by a levelling up of the cost of ICs within a logic family. The earlier years (1959–1969) were characterized by sharp cost differentials. It was not uncommon to find that the cost of a more sophisticated MSI was about 30 times that of a basic logic gate. Since then there has been a marked tendency for a reduced spread of costs within a digital logic family. Large-scale production has made this possible, and the standard ICs, to repeat a point made earlier, have been used relatively inefficiently in numerous applications for reasons of system economics.

1.3. VLSI

The continuing increase in component and function density per chip leading from SSI to MSI and on to LSI was first utilized to increase the function density of identical or at least very similar circuits. For example counters would contain more stages giving a higher maximum count and