Tutorial Guides in Electronic Engineering

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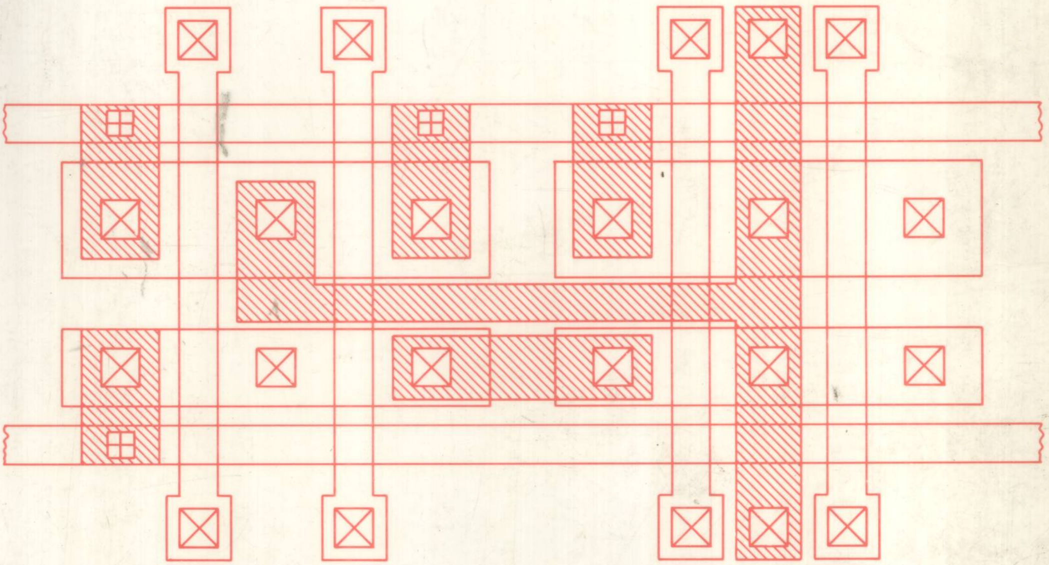
Integrated Circuit Design and Technology



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Chapman and Hall

Integrated Circuit Design and Technology

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CHAPMAN AND HALL
University and Professional Division
LONDON • NEW YORK • TOKYO • MELBOURNE • MADRAS

UK Chapman and Hall, 11 New Fetter Lane, London EC4P 4EE
USA Van Nostrand Reinhold, 115 5th Avenue, New York NY10003
JAPAN Chapman and Hall Japan, Thomson Publishing Japan, Hirakawacho Nemoto Building, 7F, 1-7-11 Hirakawa-cho, Chiyoda-ku, Tokyo 102
AUSTRALIA Chapman and Hall Australia, Thomas Nelson Australia, 480 La Trobe Street, PO Box 4725, Melbourne 3000
INDIA Chapman and Hall India, R. Sheshadri, 32 Second Main Road, CIT East, Madras 600 035

First edition 1990

Typeset in 10/12pt Times by Best-set Typesetter Ltd, Hong Kong
Printed in Great Britain by Richard Clay Ltd, Bungay, Suffolk

ISBN 0 412 34220 0 0 442 31188 5 (USA)
ISSN 0266-2620

British Library Cataloguing in Publication Data

Morant, M.J.
Integrated circuit design and technology.
1. Electronic equipment. Integrated circuits
I. Title II. Series
621.381'73

ISBN 0-412-34220-0

Library of Congress Cataloging-in-Publication Data

available

Integrated Circuit Design and Technology

TUTORIAL GUIDES IN ELECTRONIC ENGINEERING

This series is aimed at first- and second-year undergraduate courses. Each text is complete in itself, although linked with others in the series. Where possible, the trend towards a 'systems' approach is acknowledged, but classical fundamental areas of study have not been excluded. Worked examples feature prominently and indicate, where appropriate, a number of approaches to the same problem.

A format providing marginal notes has been adopted to allow the authors to include ideas and material to support the main text. These notes include references to standard mainstream texts and commentary on the applicability of solution methods, aimed particularly at covering points normally found difficult. Graded problems are provided at the end of each chapter, with answers at the end of the book.

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Preface

Until a few years ago, all integrated circuits were designed by specialists behind the closed doors of the semiconductor industry, manufactured only in enormous quantities, and sold as standard products. A remarkable change has been brought about by the development of semi-custom design techniques and CAD tools that nowadays enable all electronics engineers to design their own **application-specific integrated circuits** (ASICs) and get them made economically in small quantities. As a result, ASICs have become the key components in electronic products of all types.

This is a book about integrated circuit design and its fundamentals in silicon technology. It is **not** a manual of how to do design using any particular CAD tools, but rather, the background for all of them. IC design started to become an academic subject with the publication in 1980 of the famous book by Mead and Conway which led to the first postgraduate courses in full-custom design in the UK. Since then, ASIC design has rapidly moved into the core of many higher education courses in electronics, aided by the provision of CAD hardware and software that nowadays enable undergraduates to gain practical design experience. With such a rapid development, courses in IC design inevitably contain a rather diverse mixture of computer techniques and parts of more traditional digital and circuit design courses with EA1 and EA2 undertones! It is, of course, all these and more.

ASICs are very often designed using semi-custom methods which require absolutely no knowledge of circuits or silicon. However, the view taken in this book is that the *educated* engineer should understand at least the fundamentals of the circuit and fabrication technologies that have an impact on design and underlie all design decisions. It therefore attempts to fit integrated circuit design into a coherent framework based on the outstanding achievements of silicon technology. IC design provides an excellent opportunity for bringing together interests in semiconductors, digital and analogue circuits, and systems. Although the book tries to be self-contained, it is therefore based on the background of digital and circuit electronics that most students acquire in the first year of a degree or higher certificate course.

The core of the book in Chapters 7–9 describes the essential steps in both semi-custom and full-custom design, and the use and features of the CAD tools required to turn a chip specification into a verified, testable circuit on silicon. The earlier chapters are on IC device structures and how they are made on silicon. Chapter 4 presents the fundamentals of MOS circuits, which can be regarded either as background for semi-custom or the basis of full-custom design. Emphasis is placed on digital CMOS circuits and their design which are most likely to be met in practice, but the book also includes an introduction to analogue CMOS design for mixed analogue–digital circuits. Chapter 5 gives the background of bipolar circuits that will never be completely overshadowed by CMOS.

The book is intended to be an introductory guide to the subject in a rather different sense from other volumes in this Series. It is a guidebook to a country and, for the parts you want to visit, you will need the more detailed information given in CAD manuals, ASIC data books, and more specialized textbooks. In visiting any new country it is useful to know some of the language and I have deliberately introduced some of the established jargon of the semiconductor and CAD industries. I have also had to use centimetre rather than metre units because they are universally used in the industry.

Large parts of this book are descriptive rather than quantitative. It therefore differs from others in the Series in having only a few problems at the ends of chapters. I have omitted problems rather than trying to pretend that short hand calculations can make any real contribution to IC design. Lecturers should have no difficulty in devising CAD projects tailored to the particular hardware and software available and the students' competence in using them. Semiconductor data books can suggest design projects of any difficulty from a few gates to LSI functions, and it is particularly instructive to try to improve on the speed of standard TTL functions by designing them in CMOS. Other design projects will be suggested by courses in communications, computer systems and instrumentation.

My view of IC design, as presented in this book, has developed over the last nine years of teaching the subject in an M.Eng/M.Sc course to which the students and many leading electronics companies have contributed greatly. Too many people have been involved to thank all of them by name, but Simon Johnson has been particularly helpful, not least by providing the well-tried design exercise and some of the figures. I also wish to thank Professor Peter Hicks of the Electronics and Electrical Engineering Department, UMIST, and Professor Tony Dorey, the Consulting Editor, for many constructive comments. Parts of the book were written while I was a Senior Research Fellow at the University of York and I would particularly like to thank the Electronics Department there for their hospitality.

Contents

Introduction: Integrated Circuits – Complexity and Design

1

Reading this chapter should enable you

- ☐ To get an overview of the main topics that will be developed in the book and an appreciation of the importance of IC design as electronics 'collapses on to silicon'.
- ☐ To learn some of the terms relating to ICs in general.
- ☐ To get an appreciation of the immense *complexity* of ICs and the very small dimensions of their components.
- ☐ To get a feel for the problems that are inherent in IC design, including design cost, accuracy and testability.
- ☐ To understand the hierarchy of levels in *full-custom* IC design and the need for *semi-custom* methods.

Objectives

In the UK, software for IC design is available to all universities and polytechnics through the national Higher Education Electronics Computer Aided Design (ECAD) Initiative. Many other countries also have facilities for IC design in higher education.

Take the cover off almost any piece of electronic equipment and you will find printed circuit boards almost covered with integrated circuits of many shapes and sizes. What you see are, of course, only the packages protecting the individual silicon chips and connecting them to the board. If you were to open up the packages you could see the chips themselves but you would need a high-power microscope to see the actual circuits on the exposed surface of the silicon.

The first reaction on seeing the very fine detail of an integrated circuit as in Fig. 1.1 is, 'How incredible! How was it made?' or, for those of a scientific frame of mind, 'How does it work?' Engineers should ask, 'How ever was that designed?' This book is intended to provide some answers to that question.

What is an IC?

We will use 'IC' and the colloquial term 'chip' for 'integrated circuit' throughout this book.

Before considering design itself we need to be familiar with some of the words used in talking about integrated circuits, or ICs, in general. We should start by explaining just what the term 'integrated circuit' means to systems, design and semiconductor engineers.

To a systems engineer an integrated circuit is an electronic component used for processing signals in a particular way. Integrated circuits are the building blocks for nearly all electronic systems. Many of them carry out digital functions such as counting or storing digital data, or manipulating it under program control as in a microprocessor. Some, including op amps and many communications circuits, handle analogue rather than digital signals. Others perform both analogue and digital functions, often including A/D and D/A conversion on the chip. To use any type of IC we must be able to understand its electrical specification which will enable us to work out how it will function in a system. The specifi-

An IC on a single chip of silicon is strictly called a **monolithic** IC. **Hybrid** ICs contain several silicon chips and other components interconnected on a ceramic substrate and packaged in an hermetically sealed module for special applications.

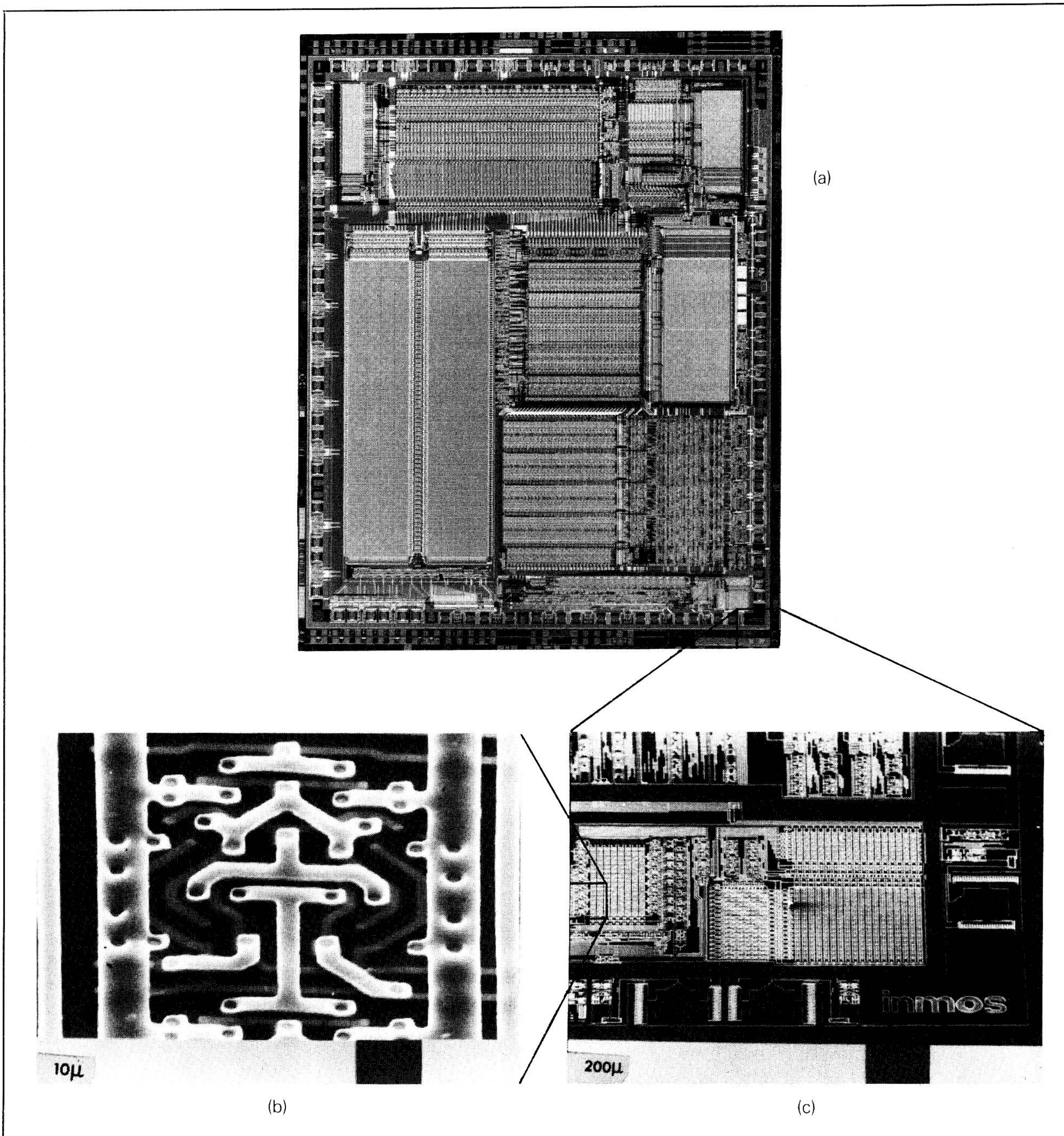

Fig. 1.1 (a) The Inmos T-800 Transputer. This is a truly VLSI integrated circuit made by a 1.2 μm CMOS process on a chip size of 8.5 × 9.5 mm and containing about 400 000 gates. (b) Scanning electron micrograph of the bottom right-hand corner of (a). The marker indicates 200 μm. (c) A further enlargement of part of (b) with the marker now indicating 10 μm. At the scale printed in (c) the entire chip would occupy about 5.3 × 5.9 metres (Courtesy of Inmos Ltd.).

cation, as given in a semiconductor data book for example, is concerned only with the external properties of an IC and this is adequate since its internal operation is largely irrelevant to systems engineers.

To design ICs, however, we need to look inside the package. At this level an IC is an electronic circuit made entirely on the top surface of a thin rectangular piece of single-crystal silicon called a 'die' by the manufacturers or, more colloquially, a 'chip'. The pattern of very small shapes in the various layers on the silicon surface, part of which is shown in Fig. 1.1(b), defines all the transistors and internal connections of a complete circuit. Fairly simple ICs typically contain a few thousand interconnected transistors and the most complex ones a million or more. Each transistor is extremely small and they are packed very closely together on the silicon surface so that a highly complex circuit can be fitted on to a chip only a few millimetres square. Fine wires, welded to contact pads around the edge of the chip, carry signals between the circuit and more substantial connections on the package, and hence to a printed circuit board.

The term 'chip' is misleading. It always reminds me of a chip of flint! The chips are, in fact, sawn out of the silicon very precisely.

Details of IC packages are given in Sangwine (1987).

Integrated circuits are manufactured by the semiconductor industry using extremely advanced and exciting 'fabrication technologies' which have their scientific foundations in applied physics and chemistry. A long sequence of fabrication steps is used to build up the layers on the silicon and to etch them into the shapes required to form the transistors and interconnections. Each step has to be precisely controlled to give the best circuit performance and the complete sequence, known as a fabrication **process**, is highly optimized or 'tuned' for the efficient production of a particular class of ICs. The design of an individual chip to be made by this process is contained entirely in the complex pattern of shapes, called the **layout geometry**, that is to be fabricated on the silicon. This is the semiconductor engineer's view of an integrated circuit.

The systems and semiconductor views of an IC are completely different and it is the design engineer who is concerned with the link between them. All design is the process of turning a basic, abstract idea into reality. In this case the idea is the system specification and the product is the piece of silicon and a few other materials which, almost miraculously, implements it as hardware. The design and manufacturing processes bring about this transformation. The designer must therefore know something about how the IC will be used and also about how it will be made, although he is concerned primarily with creating the link between specification and fabrication. There are many levels in this link such as those concerned with algorithms, sub-systems, logic, circuits and layout so that the designer has to take a very broad view of what is meant by an IC. This view is the main concern of this book.

Standard-product ICs and ASICs

Examination of the type numbers printed on the packages of ICs in any piece of modern electronic equipment will show that only some of them are recognizable as devices listed in semiconductor manufacturer's catalogues. These are standard-product or catalogue ICs produced in very large numbers and widely marketed as building blocks for a great range of applications. The others are ICs that have been designed for one particular application and called **application-specific ICs** or ASICs.

Standard ICs are the basic products of the semiconductor industry. They

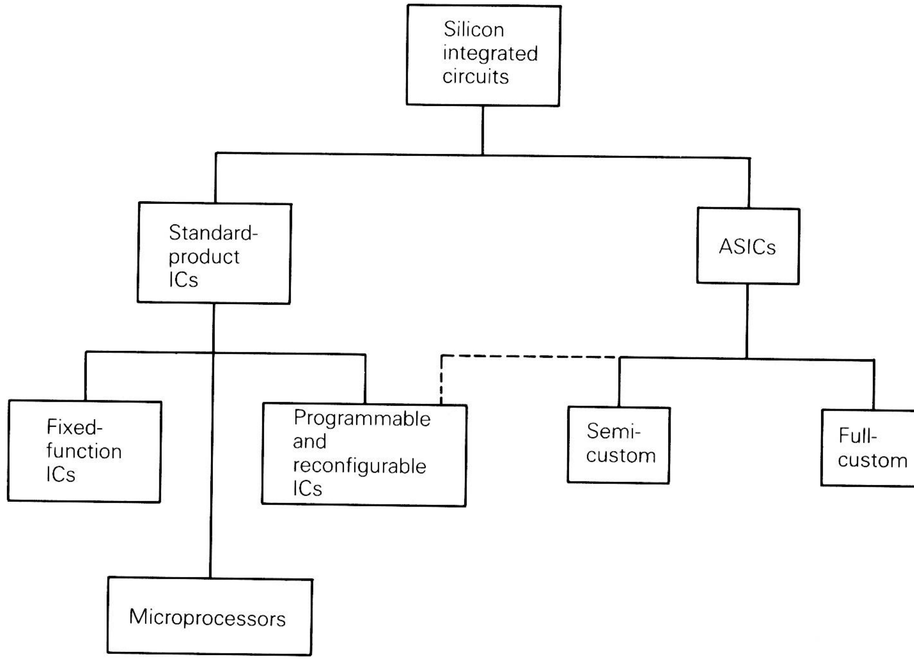

Fig. 1.2 Routes to integrated circuits for building digital systems.

Mass production usually implies quantities of more than a million chips in the production life cycle of a particular design. Memory chips are produced in the largest numbers. One large Japanese manufacturer is reported to be making 10 million, 1 Mbit DRAMs per month at present.

ASICs are usually fixed-function ICs because they are designed for one specific job.

provide the general-purpose digital and analogue functions required in such large numbers by the electronics industry that their cost is kept low by mass production. Many standard ICs are designed to carry out a single fixed function such as digital counting, binary addition, or amplification, although the exact function can often be changed by setting up appropriate control inputs. Standard ICs also include microprocessors which are far more flexible as they can carry out a whole sequence of different functions under the control of a software program, although at a comparatively low speed.

A third group of standard-product ICs are **user-programmable** chips that are electrically programmed after manufacture to carry out a fixed function for a particular application. Many of these can be classed as **programmable logic devices** or PLDs, in spite of the different names used by some manufacturers. Although they are not strictly designed by the user, the ways in which they are programmed have many similarities to ASIC design and we will consider them briefly in Chapter 6.

At first sight it is surprising that there is any need for ASICs in addition to the thousands of types of standard IC described in semiconductor data books. However, one of their main advantages is that a single ASIC may well replace many standard ICs for a particular application. This greatly reduces the cost of manufacturing electronic systems so that ASICs are now commonly used in new products. As a result, most electronic equipment companies now design their own ASICs whereas in the past IC design was entirely the province of the semiconductor industry. This explains why there is now so much interest in IC design in general.

The semiconductor industry is continually bringing out new and improved standard-product ICs made possible by advances in fabrication technology. It takes a great deal of time to design standard-product ICs for maximum performance so that the design cost is extremely high but it is easily recovered when chips are to be produced in enormous numbers. For ASICs however, the design cost is crucially important because of the relatively small number of chips used in the lifespan of a particular piece of equipment to be produced by a single company. The quantity required many only be a few thousand compared with the millions of chips produced for a standard-product design. ASICs therefore only became economical when design costs were reduced by developing new design methods and powerful computer-based design tools. Computer-aided design (CAD) has therefore become as important as fabrication in enabling silicon technology to be widely used. With suitable CAD methods, including **semi-custom** design, ASICs can be designed reliably in far less time than for comparable standard-product ICs, but with some loss of performance. We will have a lot more to say about such methods in Chapter 8.

The cost of design is at least twice as much as the wages of the engineer doing it because of company overheads such as premises and computers. A few weeks' work can therefore add substantially to the total cost of producing perhaps only a few thousand ASICs.

The second problem that had to be overcome before ASICs could become really economical was to reduce the cost of fabricating the relatively small number of chips of the same design that are required for a single application. We will find out more about the cost of producing chips in Chapter 3 where we will see that the low cost of standard-product ICs is partly due to the mass production of each design. For ASICs the cost of fabricating a small number of chips of the same design is reduced by using particular chip architectures, such as **gate arrays**, and other methods that will be described in Chapter 6.

The overall effect of developments in the semiconductor and CAD industries is that the electronics designer now has the wide choice of ways of obtaining ICs for building systems that are summarized in Fig. 1.2. It is important to make the right choice between fixed-function or programmable standard-product ICs, microprocessors, or ASICs for every part of a system. To do this we need a good understanding of integrated circuit technology and of the various ways in which ASICs can be designed.

The Complexity of ICs

Photographs such as those in Fig. 1.1 show that ICs can be extremely complicated. The smallest shapes are associated with transistors and the complexity of an IC can be measured approximately by the number of transistors it contains. Many of the more complex chips are for digital applications and complexity can then be expressed very roughly in terms of an equivalent number of two-input gates, each regarded as four transistors. A **level of integration** can be used to classify ICs by their complexity. Although not precisely defined, the terms in Table 1.1 are commonly used for indicating the complexity of digital ICs. The upper limit of VLSI complexity is still increasing every year but chips containing more than 50 000 gate equivalents are now produced in increasing numbers. They have at least 1000 times as many transistors as in the SSI and MSI chips used in elementary electronics.

A bistable may be taken as equivalent to four or eight gates according to type.

Every transistor in an IC carries out a particular job which contributes in a small way to the overall function. With a large number of transistors acting together, the complete IC can do some very complicated digital processing. The equivalent of a few hundred gates is sufficient for the simpler digital functions

Table 1.1

		Number of gate equivalents/chip
Small-scale integration	SSI	<10
Medium-scale integration	MSI	10–100
Large-scale integration	LSI	100–10 000
Very-large-scale integration	VLSI	>10 000

Unfortunately the term 'VLSI' is commonly used nowadays for far simpler chips.

such as the counting, addition, or multiplication of binary numbers. An eight-bit microprocessor can be made with a few thousand gate equivalents, an advanced 16-bit one requires a few tens of thousands and so on.

Even with only a few thousand gates, the complexity of the chip behaviour becomes nearly as difficult to comprehend as the complexity of the appearance. Complex ICs are best regarded as systems in their own right, and the user may be completely unaware of the individual gates and bistables, let alone the transistors, that contribute to its overall function. The designer, however, has to understand the detail in order to build up all the elements into a complete system. One of the main problems of digital design at this level is in the handling of large amounts of information on both the electrical behaviour and the geometry of the chip. Computer systems are obviously essential for handling this information.

The functions of most analogue integrated circuits such as filters or amplifiers are usually less complex and easier to understand. Analogue ICs tend to use far fewer transistors, rarely more than a few thousand or so, but they swap the complexity of digital circuits with the need for precision in the signal voltages and currents. Analogue design therefore presents rather different problems from digital design and these will be discussed in Chapter 10. Chapters 7–9 will be concerned largely with the design of digital ICs where complexity is nearly always the main problem. These two classes of design are brought together in ICs with both analogue and digital functions on the same chip and we will return briefly to these in Chapter 10.

Figure 1.3 excludes memory chips. The largest memory chips usually contain more transistors than the most complex logic ICs but we exclude them here because their design and production has become a highly specialized branch of the semiconductor industry. Also the regular layout of memory chips enables the transistors to be packed together far more tightly than in general-purpose chips.

The increasing complexity of the most advanced digital ICs available each year has been brought about by continuous refinement of the manufacturing technology. The story of the growth in the number of transistors that can be produced on a single chip of silicon is well known. As shown in Fig. 1.3(a), the earliest ICs in 1961 contained about 10 transistors. By the early 1990s, ICs with more than a million transistors will be commonplace, and a steady increase can be expected well beyond that. Such chips represent the leading edge of microelectronics production technology, but they do not reduce the need for far larger numbers of simpler types, right down to MSI sizes, that are quite adequate for many applications.

The logarithmic annual increase in complexity was first noted in 1964 by G. Moore who later became a founder of Intel Corporation. It has continued ever since then, as predicted, although with a slightly lower slope than in the early years.

In technological terms, the increase in the maximum complexity of ICs has been made possible:

1. By reducing the size of the individual transistors, and
2. By increasing the maximum size of chip that can be manufactured economically.

In design, it has only been possible to cope with this rise in complexity by equally dramatic advances in CAD.

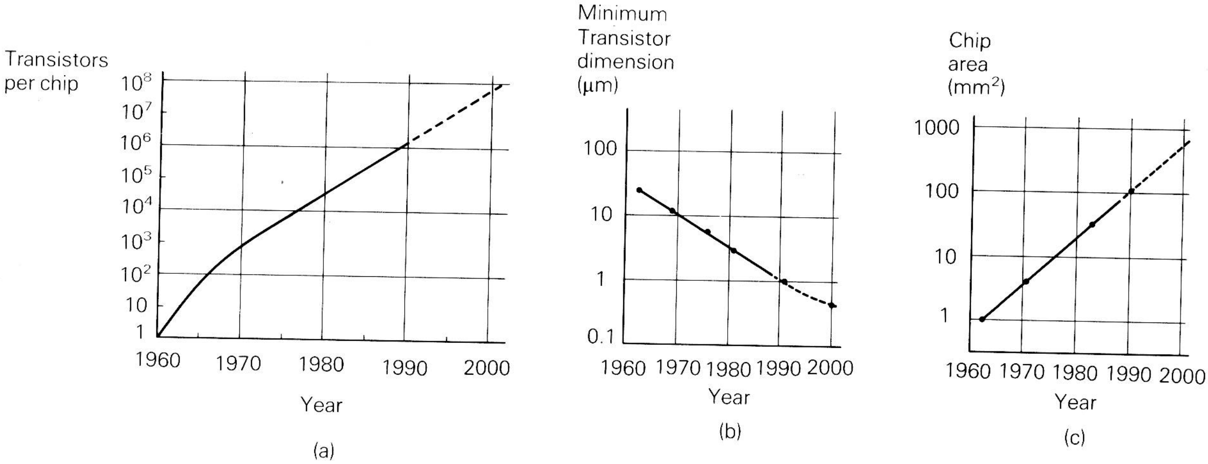

Fig. 1.3 (a) Increase in the maximum complexity of digital ICs from 1961, (b) the minimum feature size of their transistors, and (c) the maximum chip area. Diagrams like these are frequently published but it is not always made clear what type of chips they refer to. Here it is for logic ICs that are in sufficiently large-scale production to be readily available. Memory chips and ICs under development (and sometimes already advertised!) may be considerably more complex.

To appreciate the achievements of fabrication technology we need to have a feel for the dimensions of the transistors and other components in an integrated circuit. The sizes are usually expressed in micrometres or microns. A micron is one thousandth of a millimetre and well below any length we can relate to directly – a hair from your head has a diameter of about 60 μm for example. It is nowadays possible to make parts of transistors with well-controlled widths of one micron or less.

The micrometre (10^{-6} m = 10^{-4} cm) is called a **micron** in the semiconductor business. The smallest particle visible to the naked eye with good illumination has a diameter of about 40 μm.

Figure 1.3(b) shows how the dimensions of the smallest transistors in production have fallen as the fabrication technology has been refined. As a result of a tremendous amount of research and development the already-small sizes were reduced by more than 20 times in about 25 years and further reductions are made every year as the technology becomes even more advanced.

Making transistors smaller has two great advantages for ICs. The first is that circuits operate faster as the transistors are scaled down so that some digital ICs for example now work at clock frequencies of at least 100 MHz. The second is that the cost of producing ICs does not rise greatly with the density of transistors, that is the number per square millimetre, that they contain. By shrinking the dimensions, the cost per transistor therefore falls rapidly. With smaller dimensions, closer packing, and other technological improvements the cost of transistors on large ICs did, in fact, fall by about 10^4 times in the first 25 years of silicon chip production. The continuing increase in packing density also explains how it is possible to produce more and more complex chips each year with only small increases in cost. Reducing the transistor size has been the largest single factor in bringing about the explosive growth in the use of electronics which has been called the Information Revolution. The trend will certainly continue for many more years before fundamental limits to the minimum size are eventually reached.

The electrical characteristics change as transistors are made smaller. A point will be reached where they become either unusable or subject to unacceptably large statistical variations, but the limits have not yet been identified with certainty.

The second development leading to even more complex digital ICs has been the steady increase in the maximum size of chips in large-scale production which is shown in Fig. 1.3(c). How this has come about will be explained in Chapter 3 when we consider some of the economic aspects of chip fabrication that are important for design. We will find that, in general, the cost of chip fabrication in large-scale production rises only slowly with complexity so that the cost per gate is reduced dramatically by increasing the level of integration. This is the stimulus driving the semiconductor industry to greater and greater complexity. For the systems designer it means that it is often cheaper to use a single complex IC rather than several smaller ones.

One of the problems that had to be faced by the semiconductor industry some years ago was that, while it was possible to mass produce more and more complex chips, it became increasingly difficult to find general-purpose functions that were likely to be required in sufficiently large numbers to bring the prices down. As complexity rises the functions produced become more specialized and demand falls. The first large uses for LSI were therefore in new applications such as calculators and watches. The demand for even more complexity, and eventually VLSI, was later created by the development of standard-product microprocessors that could be mass-produced and sold in very large numbers because of the wide range of applications made possible by software programming. More recently, large-scale specialized applications have been found for standard-product VLSI in communications, computers and signal processing, although the need for general-purpose building blocks is falling with the increasing use of ASICs.

These have been called **application-specific standard-product** (ASSP) ICs.

The overall effect of developments in silicon fabrication technology is that the ever more complex ICs produced each year lead to even more powerful information systems, opening up entirely new application areas for electronics. However, although electronics itself can be said to be collapsing on to silicon, the increasing complexity does raise some really challenging technical problems, particularly, as we shall see, in the area of IC design.

The Problems of Design

In order to get the most benefit from silicon fabrication technology we must be able to design ICs efficiently and quickly. Nearly all the problems in designing digital ICs are ultimately due to complexity. The first, and probably most important problem, is how to reduce the time taken in designing complex circuits. It is obvious that we cannot design a circuit containing say 20 000 transistors one transistor at a time! Even if it was technically feasible, it would be prohibitively slow and expensive so that we have to find better ways of dealing with the complexity.

We have already seen that the time spent on design is crucial because its cost can add appreciably to the final cost of the chips even when moderately large numbers are to be produced. For example, it might cost £50 000 to design a standard IC containing 5000 gates, and this would add 20p to the cost of each chip for a production run of 250 000. If the design cost was proportional to complexity it could rise to £1M for a similar IC containing 100 000 gates and this would have to be covered by a far larger production run. A low and predictable design time is particularly important for ASICs where it may account for a large proportion of the total cost.

Design cost depends very much on the complexity of the chip function. It is certainly possible to design a 5000-gate ASIC for far less than £10 000 if its function is well understood at the start.