**Fundamentals of Integrated Circuits.** (Motorola Series in Solid-State Electronics)

Fundamentals of Integrated Circuits

# Fundamentals of Integrated Circuits

**MOTOROLA SERIES IN SOLID-STATE ELECTRONICS**

*Integrated Circuits: Design Principles and Fabrication*
*Analysis and Design of Integrated Circuits*
*Fundamentals of Integrated Circuits*

# *Preface*

In the few years since the philosophy of integrated circuits was first expressed, progress in the development, the manufacture and the use of these devices has been phenomenal. Already, integrated circuits account for roughly 25 percent of the total dollar market for semiconductor components, and substantially further inroads are anticipated in the years ahead.

It is significant, however, that most of the products emanating from this technology have been directed toward and absorbed by a single segment of the electronics industry—the computer market. The vast consumer products market, the potentially huge automotive electronics segment, the diversified controls field—in fact, most areas of applications requiring functions other than the digital logic and switching functions—still remain essentially untapped.

There is no reason, of course, why integrated circuits cannot bring to other markets the same benefits of reduced cost, improved reliability, etc., that have made them the foundation for the manufacture of data processing equipment. Indeed, with digital technology firmly committed to integrated circuits, manufacturers are directing more research and development efforts toward linear circuits than ever before. It is a safe prediction that by the early 1970's the entire industry will be so heavily dependent on integrated circuits that acquaintance with the principles and practices of this technology will be a prerequisite for everyone working in the electronics field.

The purpose of this book is to bridge the gap between the design and marketing concepts associated with discrete-component equipment and the new considerations involved in the use of integrated circuits. Technically, it discusses the various techniques of integrated circuit fabrication and their strong influence on circuit design and performance. From a marketing viewpoint, it compares the relative qualities of the numerous integrated circuit structures the technology has devised in terms of ultimate economics and logistics. Thus, it should serve as a transitional text for engineeers and technicians, as well as an introduction to this complex field for marketing and product-management personnel.

To accomplish its objective, Chapter 1 presents an overview of the integrated circuit art, introducing the various structures, discussing their advantages, and anticipating the effects of this technology on the various segments of the industry. This is followed by three chapters concerning the basic principles of semiconductor electronics and their relationships to integrated circuits. Chapter 2 discusses the properties of silicon as a semiconductor material; Chapter 3 explains the p-n junction, whose characteristics influence both the design and performance of diffused circuits; Chapter 4 describes the operation of the transistor, which represents the basic structure of the monolithic technology. No attempt is made to delve deeply into the theory of semiconductor design. Only those aspects that the author considers important to the understanding of integrated circuits are detailed and, for the most part, the discussion is qualitative rather than quantitative. The mathematics that is employed is held to simple algebra and the equations are subsequently explained, with emphasis on their important components.

Without question, the most prevalent type of integrated circuit today is the diffused monolithic circuit. The fabrication details and the various processes involved in the construction of such circuits are described in Chapter 5. This is followed by a detailed discussion of the characteristics of diffused components, including their parasitics and their design considerations.

The component characterstics and fabrication sequences for thin-film circuits are described in Chapter 6, while Chapter 7 gives similar information for other types of integrated structures including multi-chip circuits, compatible circuits, monobrid circuits, and insulated-substrate structures.

Packaging has been a major problem in the progressive development of integrated circuits. Chapter 8, therefore, discusses the various standard packages the technology has evolved, and speculates on both circuit and system packaging for the more complex devices envisioned for the future.

Over the years, the industry has developed a large number of standard digital integrated circuits and a smaller number of devices for linear applications. Chapter 9 is devoted to the topic of standard, off-the-shelf circuits which, if they can meet a particular system requirement, represent the most economical approach to system design. In the digital area, the various logic families, including both saturating and nonsaturating logic, are discussed in terms of basic gate operation and comparisons of advantages and limitations. The linear device section begins with a discussion of the differential amplifier circuit, which has become, to some degree, an important segment of the linear technology. The design aspects of some practical linear circuits are discussed to illustrate the interdependence of circuit design and process technology.

Standard integrated circuits do not, by any means, answer the industry's total requirements. Indeed, it is generally realized that all integrated circuit manufacturers combined do not have sufficient engineering capacity and specialized design know-how to develop all of the integrated circuits the industry will need in the years ahead. Many of these circuits, therefore, will be designed in the equipment manufacturers' establishments and built in quantity by integrated circuit manufacturers. To establish a successful relationship, however, the circuit designer must be cognizant of processing effects on circuit design. Chapter 10, therefore, deals with basic considerations for integrated circuit design, discussing both the technical and the related economic aspects.

To date, the actual mask layout for integrated circuits has been considered largely the prerogative of the integrated circuit manufacturer. As the technology expands, however, it appears that equipment manufacturers are more inclined to perform some proprietary development work, including prototype device fabrication, to prove feasibility. Design engineers, therefore, must become familiar with circuit layout considerations. Basic rules for good practice in circuit layout are provided in Chapter 11.

Finally, Chapter 12 is devoted to a discussion of the much publicized era of large-scale integration (LSI), which is expected to provide yet another step-function advance in the technology. The more prominent approaches to achieving extremely complex circuits on a single semiconductor chip are explained and diagrammed to provide an insight into the problems and the proposed solutions—for the dramatic progress that has been made in the past decade simply serves as an introduction to the far more startling achievements that are envisioned for the years ahead.

The information provided in this book is based on the work and theories of a great many technical and marketing specialists who have contributed much towards furthering the state of the integrated circuits art. Indeed, to be complete, the list of contributors would have to include virtually everyone with integrated circuit responsibility at Motorola's Semiconductor Products Division since 1961. The author is especially indebted, however, to Dwayne King, who provided the detailed information presented in Chapter 11; to George Needham, whose ideas are incorporated in Chapters 1 and 8 and whose suggestions for the organization of the presentation have been extremely valuable; to Les Hazlett and Walter Seelbach whose research and philosophies in the fields of computer-aided design and large-scale integration are reflected in Chapter 12; and to David Lynn and David Metz, for their critical evaluation of the technical accuracy and content of the manuscript.

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# Contents

CHAPTER 1

# A New Era in Electronics

Within the last decade we have witnessed a gradual evolution in the field of electronics which has brought us suddenly and dramatically to the threshold of a new technology . . . a technology whose impact on the industry in the coming years will be greater and more widespread than that of any development or invention since the turn of the century . . . a technology known as *integrated circuits.*

Integrated circuits in their ultimate form completely eliminate the utilization of individual electronics parts, such as resistors, capacitors, transistors, etc., as the building blocks of the electronic circuit. In their place we have tiny *chips* of semiconductor material whose functions are not those of a single part, but of dozens of transistors, resistors, capacitors and other electronic elements, all interconnected to perform the task of a complex circuit, often comprising a number of complete conventional circuit stages. Within or on top of these tiny silicon chips are microscopically small depositions or growths of material layers which, while they serve the functions of the individual discrete parts, are in themselves inseparable and irreparable. Thus, a multistage amplifier, a complex flip-flop, and dozens of other functional circuits are becoming the basic components of complete electronics equipments, and every phase of the industry, from engineering to servicing, from equipment production to product marketing, is feeling the impact. Indeed, the concept of integrated circuits is so far-reaching that it is ushering in a new era in the electronics art.

## 1-1 The Technology

What, exactly, are integrated circuits? At this moment the electronics industry itself has not yet reached agreement on a precise definition. The term integrated circuit has been applied to various devices ranging from the familiar printed electronic circuit, which has for many years been in use in home radios and television receivers, to a proposed and yet undeveloped form of molecular electronics which promises the capability of, someday, drawing complete, operative amplifiers and even receivers, from a semiconductor melt. In between these extremes of a relatively old and very limited technique and one which might still be considered wishful thinking, are some highly advanced, yet thoroughly practical concepts to which the phrase integrated circuits is more aptly applied.

Actually, today's concept of integrated circuits refers to a family of devices related not so much by a common design or manufacturing method as by a series of advantages they have in common compared with conventionally wired circuits. These advantages include (1) a drastic reduction in size and weight, (2) a substantial increase in reliability, (3) the promise of substantial cost reductions, and (4) a possible improvement in circuit performance. Finally, an integrated circuit normally is composed of parts that are so closely associated with one another that repair becomes difficult, if not impossible, and in case of trouble the entire circuit is replaced as a single component.

Basically, there are two general classifications of integrated circuits—the semiconductor *monolithic* integrated circuit and the *thin-film* integrated circuit. Related to each of these basic classifications there might be a variety of structures, each with specific advantages and disadvantages from the standpoint of circuit design and applications. There are also combinations of thin-film and semiconductor circuits, i.e., thin-film component arrays on top of semiconductor circuits and semiconductor circuits on thin-film networks, that promise to combine all the various features of the individual devices in a single complex configuration of maximum utility. The present most commonly used structures, and those showing promise of implementation in the near future are listed in Table 1-1 and will be described briefly in the following sections.

**Table 1-1. Types of Integrated Circuits**

| *Basic Group* | *Variations* |
|---|---|
| Semiconductor Monolithic Circuits | Multi-chip (Hybrid) Circuits |
| Thin-Film Circuits | Monobrid Circuits |
| | Compatible Monolithic Circuits |
| | Insulated-Substrate Monolithic Circuits |

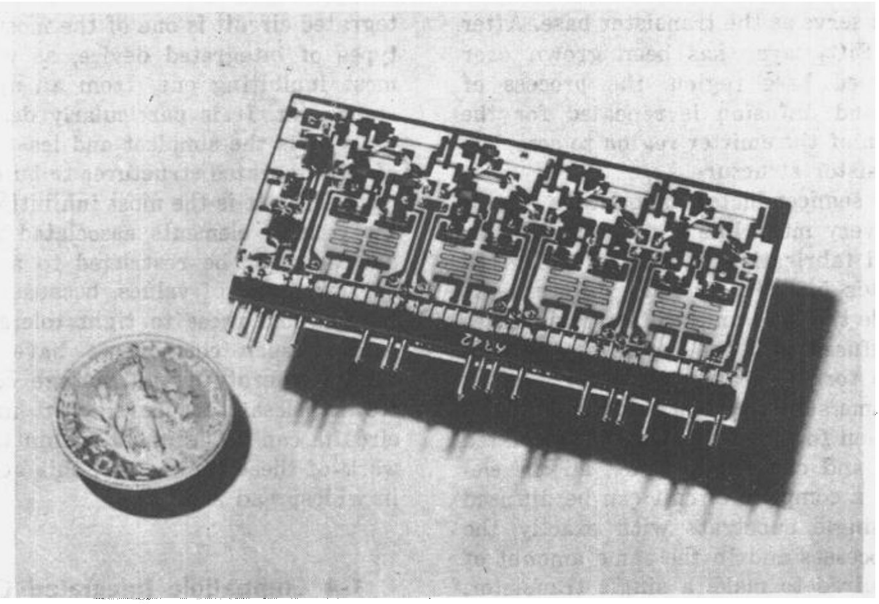
## 1-2 Thin-Film Circuits

The general classification of thin-film circuits applies to a structure that begins with a chassis, henceforth called *substrate*, made of an insulating material, such as glass or ceramic. Upon this substrate are deposited by various techniques, such as *vacuum evaporation*, *sputtering*, and *silk screening*, a pattern of the *passive elements* of the circuit (i.e., resistors, capacitors), as well as an interconnecting pattern of *metalization* that connects these elements to each other and to the *active elements* (i.e., transistors, diodes, etc.) which are needed to complete a functional circuit. These active elements are added separately to the thin-film pattern. A typical arrangement is shown in Fig. 1-1.

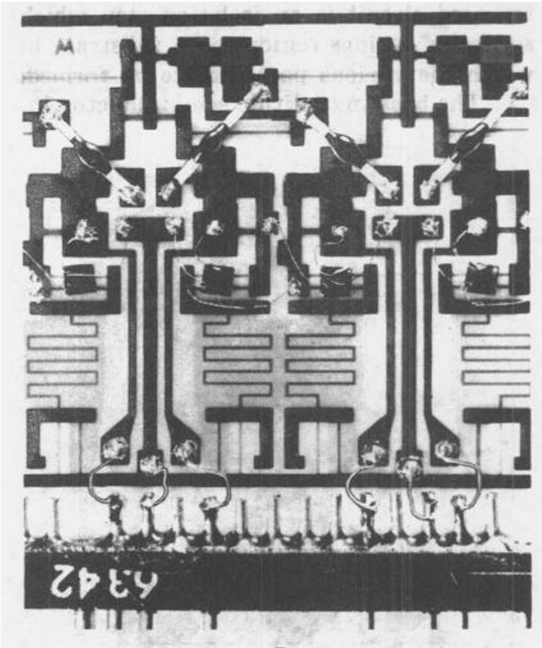
Although a number of manufacturers are working on techniques which would permit the deposition of active elements on insulating substrates by processes that are compatible with the deposition of passive elements, only limited success has been reported; no one has yet found the secret for doing this on a production basis. Herein lies the principal drawback of thin-film circuits. With the present technology, therefore, such active components are added to the pattern of thin films in *discrete* form. True, these discrete components are extremely small and add only slightly to the overall size of the completed device, but they do require additional production steps which reduce manufacturing *yield*, increase costs, and adversely affect the ultimate reliability of the completed circuit.

Nevertheless, thin-film circuits are being produced and utilized in equipment already on the market, and in new equipment now in production. In comparison with conventionally built circuits, using all discrete components, they are smaller, less expensive and, potentially, more reliable. In comparison with semiconductor monolithic circuits, discussed below, they are more flexible, and permit the fabrication of parts with closer tolerances. In addition, the training of design personnel is a relatively simple matter. Indeed, if processes are developed for the compatible deposition of both active and passive elements with thin-film techniques, the future of thin-film circuits is bright indeed.

The technology of semiconductor integrated circuits, however, has developed far more rapidly than that of thin films. Already, the limitations of the earliest semiconductor networks have been overcome in the laboratories and new techniques are being adopted for mass production. These new techniques utilize thin-film processes



(A)



(B)

FIGURE 1-1. *Typical of thin-film circuits is this 16-to-1 frequency divider (A). Passive-element film patterns are deposited on a ceramic substrate and microminiature active devices (B) are added separately in discrete form.*

to supplement basic semiconductor circuits, thus combining the best features of both technologies. Principally, it is the low-cost, large-quantity production feasibility of semiconductor monolithic circuits that constitutes the main advantage of such devices.

## 1-3 Semiconductor Monolithic Circuits

The basic semiconductor integrated circuit is a monolithic device; i.e., all elements associated with the circuit are fabricated inseparably on or within a continuous piece of material. See Fig. 1-2. In the case of today's circuits, this material is silicon, which serves as the substrate for a monolithic device.

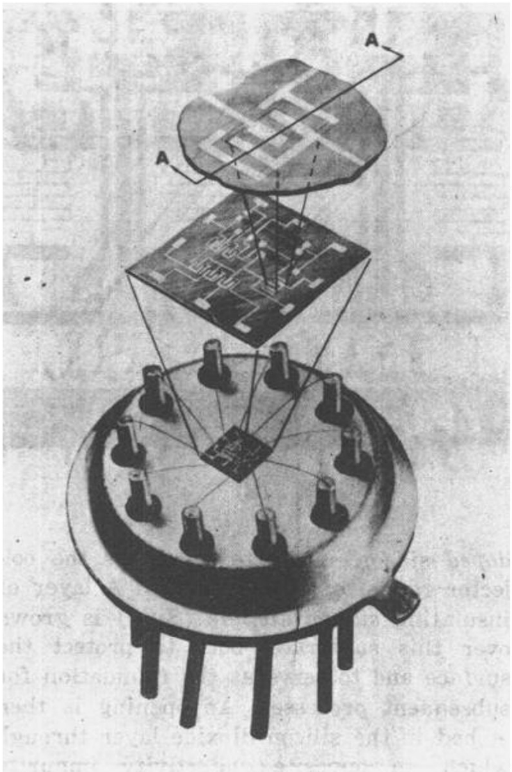
The semiconductor monolithic integrated circuit is made with a sequential series of *masked diffusion* and *oxidation* processes identical to those used in the fabrication of today's surface passivated transistors. In such transistors, a suitably *doped* silicon substrate serves as the collector region of the transistor. A layer of insulating *silicon dioxide* ($SiO_2$) is grown over this substrate, both to protect the surface and to serve as the foundation for subsequent processes. An opening is then etched in the silicon dioxide layer through which an opposite-conductivity impurity material can be diffused into the collector region to serve as the transistor base. After another $SiO_2$ layer has been grown over the exposed base region, the process of etching and diffusion is repeated for the formation of the emitter region to complete the transistor structure.

The semiconductor monolithic circuit is made very much like a single transistor. (Detailed fabrication procedures are given in Chapter 5). The primary difference is that while the base and emitter regions are being diffused into one region of the substrate to form a transistor, other regions of the same substrate are being acted upon by diffusion for the formation of associated resistors and capacitors. Thus, all the elements of a complete circuit can be diffused into a single substrate with exactly the same processes and in the same amount of time required to make a single transistor. The one additional step required for the integrated circuit is an isolation step which separates various regions on a substrate in which the various parts are to be formed.

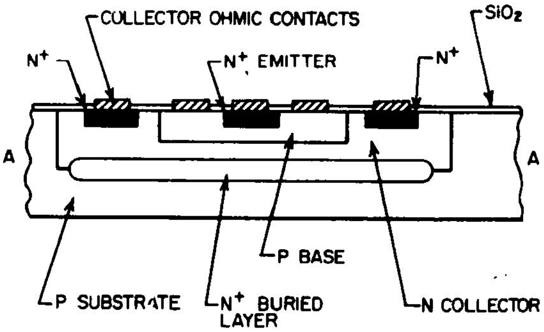
The basic monolithic semiconductor integrated circuit is one of the most desirable types of integrated device, as well as the most inhibiting one, from an applications standpoint. It is particularly desirable because it is the simplest and least expensive of all integrated structures to build in large quantities. It is the most inhibiting because the passive elements associated with such devices must be restricted to a relatively narrow range of values, because it is difficult to hold these to tight tolerances, and because such components have relatively high temperature and voltage coefficients. Nevertheless, because a great many logic circuits can be designed within the framework of these limitations, this structure is in widespread use.

## 1-4 Compatible Integrated Circuits

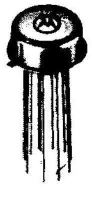
The drawbacks of the all-diffused monolithic circuit can be overcome by means of a *compatible* technique which utilizes both semiconductor and film processes. A com-




(A)




(B)



(C)

FIGURE 1-2. *Construction details of a monolithic semiconductor integrated circuit (A). This is the most prevalent type of integrated circuit in use. Cross-section of a transistor (B). Approximate size of a typical integrated circuit (C).*

patible circuit, such as that shown in Fig. 1-3, is one in which all active elements and perhaps some of the passive ones as well are diffused into a basic semiconductor substrate, and additional passive elements are deposited by film processes on top of the silicon dioxide protective layer that covers the semiconductor elements. Interconnections between the film and semiconductor elements are made by means of aluminum metallization that extends through openings etched at appropriate points in the insulating $SiO_2$ layer.

The term compatible circuits indicates that the processes used to deposit film elements on top of the silicon dioxide cannot be permitted to adversely affect the semiconductor circuit beneath. The development of suitable processes involves a careful selection of the materials used for the film elements as well as the techniques used in their deposition.

Compatible circuits combine the advantages of both semiconductor and film technologies. In common with semiconductor circuits, compatible devices are truly monolithic structures and do not require the attachment of separate discrete parts as does a basic film circuit. Thus, they should be less expensive to build in large quantities than the film circuit although they are more expensive than the all-diffused monolithic structures, because of a number of additional process steps. Compatible structures are more flexible than all-diffused devices because they can be made

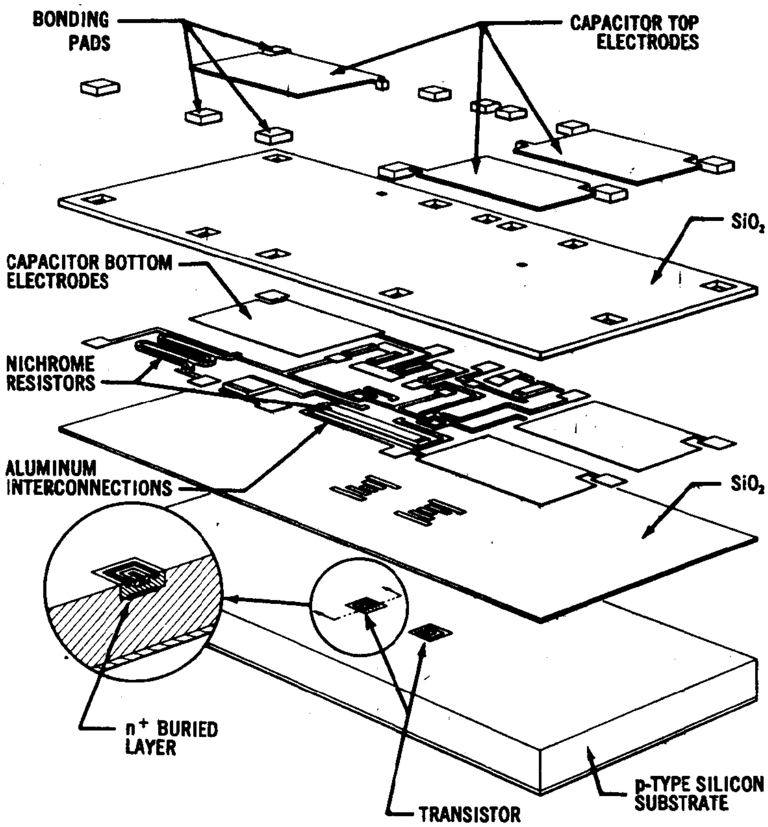



FIGURE 1-3. *Exploded drawing of a compatible circuit utilizing a combination of semiconductor and thin-film techniques. Drawing shows transistors diffused into basic semiconductor substrate, supplemented by thin-film resistors and capacitors. Isolation and capacitor's dielectric is supplied by interspersed films of silicon dioxide ($SiO_2$).*

less susceptible to the limitations that plague the passive elements of an all-diffused circuit. In the further development of the compatible circuit, therefore, lies the solution for combining the advantages of integrated circuits with the complete versatility of discrete-component circuits.

## 1-5 Multi-chip (Hybrid) Integrated Circuits

In addition to the above technologies, there is one other type of integrated circuit that is of general interest. This is called a hybrid or, more generally, a *multi-chip* circuit. See Fig. 1-4.

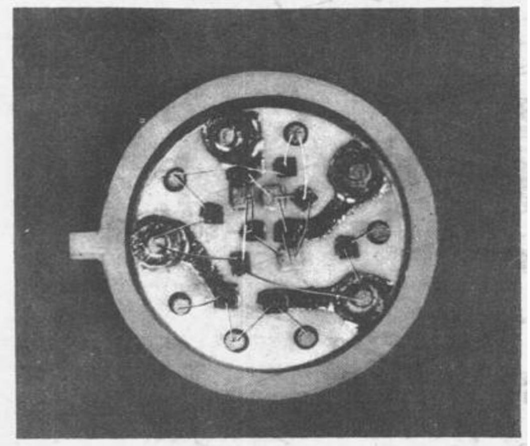


FIGURE 1-4. *Enlarged view of typical multi-chip circuit. Interconnection of separate diffused and/or film-type components make the multi-chip circuit the most versatile circuit, though certainly the most expensive one to produce in large quantities.*

The multi-chip circuit is not a monolithic device. Rather, it is composed of individual parts, made either by film or diffusion processes. These parts are attached to a ceramic substrate and interconnected by a combination of metalization processes and *wire bonding* techniques. The completed circuit may be housed in packages identical to those used for monolithic and compatible circuits.

The multi-chip circuit is particularly useful for applications where only a small number of identical circuits are required—principally for economic reasons. Whereas a monolithic or compatible circuit is made by a sequential series of masked processes, with each different circuit requiring a separate and exclusive set of masks costing hundreds to thousands of dollars, the multi-chip device is made of individual interconnected parts which, like discrete components, can be stocked in large quantities by manufacturers. Such circuits, therefore, save not only the cost involved in fabricating precision mask sets, but also permit much quicker deliveries. Both of these advantages, however, are nullified where identical circuits are needed in large (say more than 10000) quantities. This is so because, as quantities are increased, the mask-development time and cost is soon offset by the much greater time and cost involved in attaching and interconnecting a myriad of individual chips in a multi-chip circuit.

Multi-chip circuits are also ideal for the development of prototype equipment which, later, will be converted to use monolithic integrated circuits. Here the multi-chip devices have the advantage because (1) they are needed only in small quantities, and (2) design changes can be made quickly and inexpensively. (With monolithic circuits, a single design change, such as a change in a resistor value, can involve a complete redesign of the entire mask set.)

*Monobrid integrated circuits.* A variation of the multi-chip circuit is the so-called monobrid device, see Fig. 1-5, which represents a functional compromise between a monolithic and hybrid circuit. With monolithic circuits, it is a basic law that the more complex the circuit, the larger the chip must be to house the required number of circuit elements. And it is another practical law that the larger the chip, the lower the manufacturing yield; hence, the greater the cost. For very complex circuits, therefore, it is often more economical to split the circuit into two or more parts, each containing a smaller number of interconnected circuit elements. These individual chips, each of which could be described as a monolithic circuit, can then be mounted in a single package and interconnected by

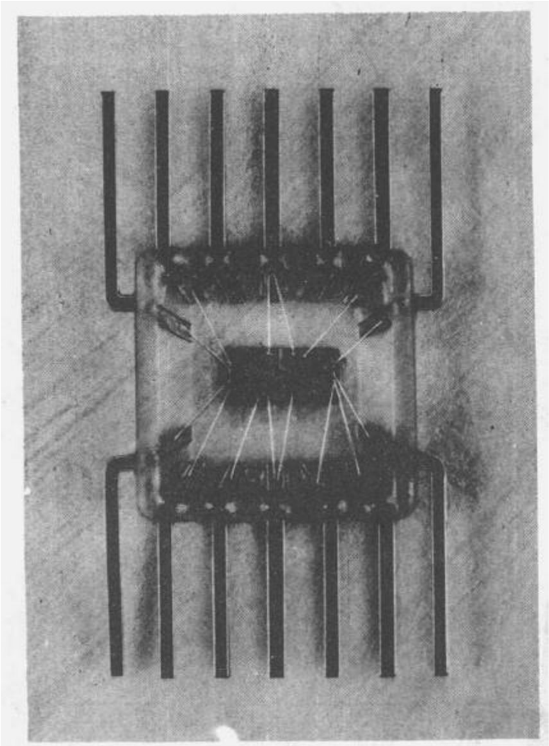


FIGURE 1-5. *Two or more monolithic circuits interconnected in a single package is referred to as a "monobrid."*

means of wire bonds—*a la* the hybrid technique. Hence, the name *monobrid.*

Additionally, monobrid circuits overcome some of the technical limitations currently associated with monolithic devices. An example of this is a circuit requiring both p-n-p and n-p-n transistors. While it is possible to develop such circuits in monolithic form, this generally involves a compromise in the performance characteristics of either the n-p-n or p-n-p transistors. With monobrid devices, the n-p-n transistor circuit may be placed on a single monolithic chip, while the p-n-p transistors and their associated parts can be fabricated in a second chip, thus permitting optimization of the electrical characteristics of both. In fact, whenever a circuit requires transistors with different characteristics, it is often more convenient and less expensive to employ the monobrid approach—as long as the number of individual chips comprising the monobrid structure is small enough that the cost of interconnecting these does not constitute the major factor of the toal device cost.

## 1-6 Insulated Substrate Monolithic Circuits

This type of structure is a variation of the basic monolithic semiconductor circuit whose feasibility has been proven in the laboratory and which is currently in development for mass production. The principal difference is in the methods employed for insulating the various components within a single semiconductor chip. Whereas the monolithic semiconductor circuit depends upon the electrical characteristics of a back-biased p-n junction to isolate the various parts, the insulated-substrate structure (see Chapter 7) actually surrounds each component with a layer of $SiO_2$ whose insulating properties are far superior to those of a p-n junction. As a result, circuit design is greatly simplified and performance at high frequencies can be substantially improved.

## 1-7 Advantages of Integrated Circuits

Although the development of integrated circuits has made giant strides forward during the past years, it is generally conceded that the entire technology is still in its infancy. While all of the integrated circuit techniques outlined above are currently in use, it is quite likely that, as further progress is made, some of these techniques will be discarded. In comparing the various technologies, it appears that the monolithic and/or compatible circuit provides the greatest number of functional features and manufacturing advantages. Thus, in comparing the integrated circuit with the conventionally wired, discrete-component circuit, we will, hereafter, consider basically the monolithic structure.

The advantages of integrated circuits over their conventional counterparts can be more clearly and precisely defined than the term integrated circuit itself. Basically, these are: greatly reduced size and weight;

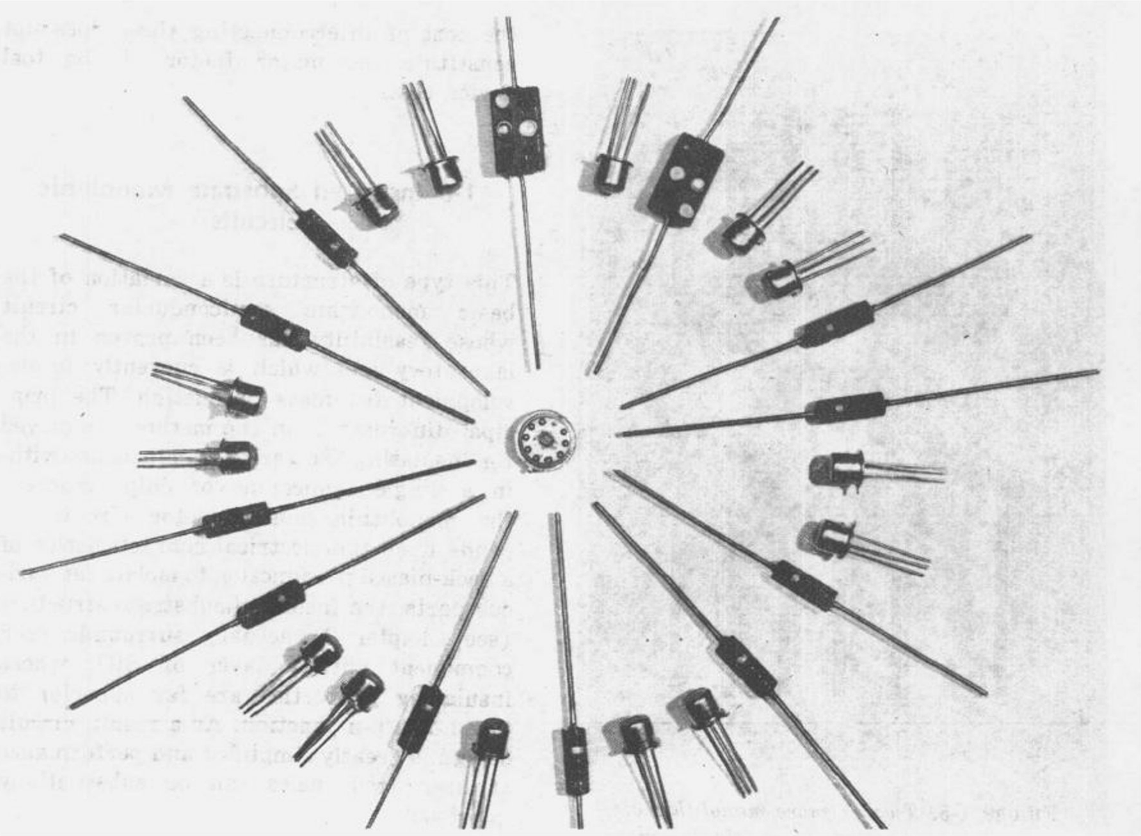


FIGURE 1-6. *Typical integrated circuit surrounded by the discrete components required to construct a similar circuit with conventional parts. Though a relatively simple circuit by today's capabilities, it, nevertheless, illustrates the space and weight savings accomplished with integrated circuits.*

lower cost; improved reliability; potentially improved performance. As we analyze these advantages individually, it will become obvious that not all of them apply to every application in which integrated circuits will eventually be used. But there is no electronic equipment that will not benefit from at least one of these. It is a safe bet, therefore, that integrated circuits will find their way into all phases of electronic equipment in a relatively short time, although some equipments may never become entirely integrated.

*Size and weight.* Of all the advantages of integrated circuits, the equipment size and weight reduction which they afford is perhaps the most obvious. This advantage is demonstrated in Fig. 1-6. With proper design and layout, the equivalent of dozens, and even hundreds, of individual parts can be deposited on or within a single chip of silicon less than a tenth of an inch square and only a few thousandths of an inch thick. These completely interconnected circuits are housed in packages similar to those used for the encapsulation of individual discrete transistors, with plenty of room to spare on the inside. Tiny flat packages, some of them no larger than ⅛ × ¼ in., are becoming more evident for applications where size and weight reductions are emphasized, but even these are much larger than the integrated circuits they contain. Although some sort of package is required to permit the interconnection of numerous integrated circuits, the technology of packaging integrated circuit equipment is still lagging far behind the technology of actually making the circuits themselves.

It is true that individual integrated circuits, such as amplifiers, flip-flops, etc.,