A User's Handbook of Integrated Circuits

Eugene R. Hnatek

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PREFACE

To really take advantage of integrated circuit techniques, at the practical how-to-do-it level, an electronics designer has to understand something about fabrication. He also must be familiar with the advantages and disadvantages of the various approaches, in order to properly select the one best suited for a particular application.

Integrated circuit selection is not a simple choice among MOS or bipolar or hybrid devices; it involves a continuous investigation of a multitude of combinations of performance, speed, operation, size, and cost. Only when the equipment designer explores all the alternatives available to him, keeping in mind that there are considerable performance–speed–cost trade-offs involved in his choice, is he likely to make the optimum selection.

The main purpose of the book is to give the practicing engineer, or the engineering student, an insight into the basic trade-offs between conventional circuits assembled from discrete components and ICs, and among the different IC families.

Much of the book is devoted to IC processing—not on the level required by a processing specialist, but on the level that a practicing engineer needs to make an informed choice among circuits made by different technologies. Each process has inherent advantages in performance, cost, and reliability. But each also imposes inherent constraints. These trade-offs are far from straightforward, since the combinations of advantages and disadvantages for each technology are unique.

There are many books on semiconductor processing, as well as many detailed design analyses of particular types of ICs. But the author has long felt a need for a handbook that presents a coordinated view of internal IC design processing and IC applications.

The book is organized in six parts:

- Chapter 1 is an introduction to all the major IC technologies and briefly compares them with discrete-component technology.

- Chapter 2 covers the processing of bipolar ICs and explains in more detail why ICs do not have the same performance characteristics as conventional circuits.
- Chapters 3 through 5 cover the design, types, and applications of digital bipolar ICs. Emphasis is placed in the applications chapter on TTL medium-scale integration, since this type of circuit dominates digital system design. This section also includes the first information published in a book on the new tri-state form of TTL and its applications.
- Chapters 6 through 9 present information on MOS arrays. Since processing technology is the main reason for the performance differences among types of MOS ICs, processing of the types is discussed in context with their performance characteristics. This section includes information on how to combine MOS with bipolar ICs to obtain the most benefit from both.
- Chapters 10 through 12 are devoted to linear bipolar ICs, specifically, operational amplifiers and voltage regulators. These represent the great majority of applications.
- Chapters 13 and 14 might be called the "do-it-yourself" section. They tell how to design thin-film and thick-film hybrid circuits, they review the processes, and they explain when each technique should be used.
- Chapter 15 covers both monolithic and hybrid packaging and assembly, including the appropriate bonding methods for use with semiconductor chip devices in a hybrid circuit.

No attempt is made to cover IC applications exhaustively, but applications of the basic types of digital and linear circuits are outlined, along with the basic rules of using them. Particular attention is paid to the "overlap" areas where a design might benefit from using more than one technology—such as MOS in combination with TTL, or monolithic ICs in a hybrid assembly.

The general applications information is designed to provide the reader with insight into the versatility of ICs. Specific devices for particular functions can then be chosen from manufacturers' literature.

Throughout the book, emphasis is placed on comparing performance and, in more general terms, the cost and reliability offered by competing IC technologies. In each of the chapter groups, simple, step-by-step guidelines and tables present the competing technologies. The guidelines and comparative information are those the author has found by experience to be most meaningful to a choice of one technology or another for a particular class of system. Once that choice has been made, the user can go to the literature for the detailed design analyses he needs to complete his design.

I should like to thank my colleagues at National Semiconductor Corp. for permission to use portions of material for the applications sections of this book, specifically, Robert Widlar, Robert Dobkin, and Dale Mrazek. Additionally, I should like to thank my typist Harford Gillaspie for her painstaking hours in preparing the drafts of this manuscript, and Charles Signor for his aid in obtaining the photographs used in this book.

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Chapter One

AN OVERVIEW OF INTEGRATED CIRCUIT CHOICES

Although there are a great many semiconductor materials in use today, silicon is preferred for integrated circuits (ICs) for several reasons. First, it is chemically simpler than compound semiconductor materials such as gallium arsenide and cadmium sulfide and therefore is not subject to stoichiometric effects of compounds. Second, silicon grows a stable oxide. Third, silicon technology is very highly developed. It is possible to grow large single crystals having very few crystalline imperfections and closely controlled impurity concentrations. Finally, although high costs are encountered in purifying silicon, they are offset by the very small amount of material used in each circuit. With reasonable yield (>50%), the fully processed semiconductor material represents considerably less than 5% of the total cost. All ICs discussed in this volume use silicon as their semiconductor medium.

CLASSIFICATION OF INTEGRATED CIRCUITS

ICs are divided into two major categories: monolithic and hybrid types as in Figure 1-1.

MONOLITHIC INTEGRATED CIRCUITS

The term "monolithic" describes an IC construction in which all the elements of the circuit are built in or on a single crystal of silicon. Because the monolithic

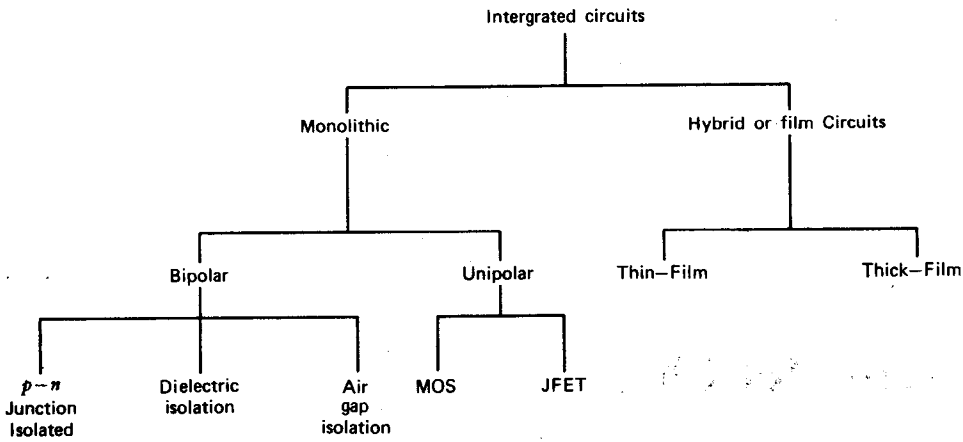

Figure 1-1 Categories of integrated circuits.

circuit layout is produced on the silicon crystal by a photographic process, such devices are easily reduced in size and may be duplicated relatively easily and cheaply. In a hybrid circuit, it is usual to find passive components such as resistors and capacitors deposited on a substrate and active elements added as discrete semiconductor "chips."

Monolithic circuits can be subdivided into bipolar and unipolar types. In bipolar circuits, charge carriers of both positive and negative polarities are required for operation of the active elements; in the unipolar case, either the positively charged "hole" or the electron with its negative charge suffices for the desired electronic function.

Bipolar elements include diodes, which have anodes and cathodes, *npn* or *pnp* transistors, which have emitters and collectors and support current flow in a particular direction, and related devices such as silicon-controlled rectifiers. Unipolar devices include various types of field-effect transistors (FETs), which can support current flow in either direction and which have interchangeable source (positive) and drain (negative) electrodes.

Bipolar Monolithic Circuits

Bipolar monolithic circuits are further subdivided according to the method used to isolate the elements from one another, electrically.

The first and still the most widely used isolation technique is the *p-n* junction method (a reverse-biased *p-n* junction resists the flow of current). However, photocurrent regeneration can break down a reverse-biased junction, making the IC susceptible to malfunction in a radiation environment. Also, the relatively large capacitances associated with isolation junctions adversely affect the speed of digital circuits and the frequency of r-f circuits.

Two other methods are dielectric isolation and air-gap isolation. "Dielectric isolation" ordinarily indicates that the single-crystal elements of an IC are surrounded by a solid dielectric—typically, silicon dioxide. In air-gap isolation, the silicon is etched between the IC components (i.e., in place of the junction isolation). Then an oxide layer is placed over the wafer. These two techniques are generally more complicated to apply and therefore more expensive than the reverse-biased *p-n* junction method. However, they tend to resist radiation better and to give faster performance.

There are many different methods for producing a given bipolar IC. The most important differences result from the following decisions:

1. Technical performance. For example, a diffused silicon resistor has 20% tolerance and a temperature coefficient between 1600 and 2000 ppm/°C; it is not adjustable. Thin-film tantalum resistors are far superior in each respect, and tantalum performance may be vital in certain key areas.
2. The method of achieving isolation between the circuit elements.
3. The choice of the types of transistors (*pnp*, *npn*, or both).

The foregoing decisions will dictate the type and resistivity of the starting silicon wafer as well as the sequence and details of the processing steps.

Figure 1-2 is schematic cross section of a bipolar IC die with reverse-biased *p-n* junction isolation. The transistor and diffused resistor are produced by diffusing an n^+ buried layer (10) in a *p*-type silicon substrate (1). Then an *n*-type silicon layer (2) is epitaxially grown on the *p*-type silicon substrate (1). Isolation of the components is achieved by a *p*-type diffusion (3) that carries down to the original *p*-type substrate. The resistor is formed by a *p*-type diffusion (4), and the base of the transistor (5) is formed at the same time. A subsequent heavily doped *n* diffusion forms the transistor emitter (6) and the contact region under the collector contact (8). The collector contact (A), the base contact (B), the emitter contact (C), and the resistor contacts (D) are formed by evaporating aluminum, etching away the metal where it is not wanted, and alloying the aluminum into the silicon. Aside from contact regions, the silicon surface is everywhere covered with silicon dioxide (7), which serves as an insulating, passivating diffusion mask. Rather abrupt steps in the oxide, as at (9), must be cut to open windows for diffusions and contacts. Where the aluminum intraconnects pass over these oxide

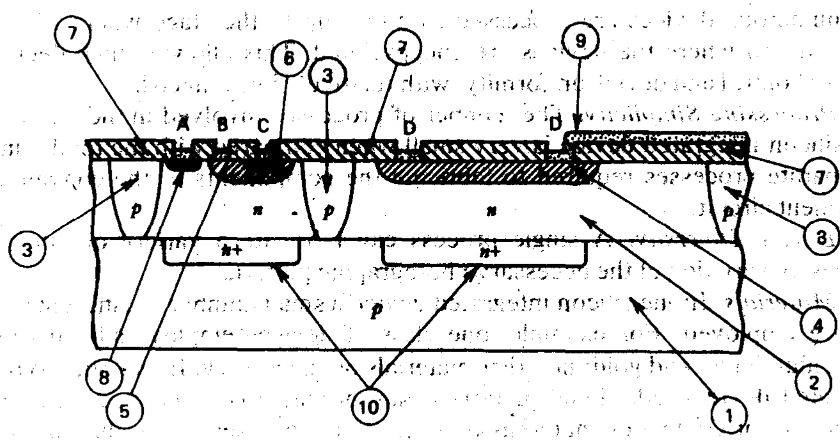

Figure 1-2 Schematic cross section of a bipolar IC die (not to scale).

steps, there is danger that the metal film will thin down and eventually open up. This is one of the weak links in many ICs.

Whereas a hybrid circuit tends to resemble a miniaturized version of a circuit built with discrete devices, the monolithic IC looks very different. This difference in appearance reflects a fundamental difference in design philosophy: It seldom makes sense to take a circuit that has performed well in discrete form and make a one-to-one transformation into an equivalent monolithic circuit. For example, economics usually pushes the discrete designer to use many inexpensive resistors in his circuit and to avoid employing relatively expensive transistors. In designing a monolithic circuit to do an equivalent task, however, the designer would probably avoid resistors and use more transistors. Resistors take up much valuable silicon area. Transistors are far more compact and easier and less expensive to fabricate.

Features of Bipolar Integrated Circuits

Power dissipation of bipolar silicon integrated devices is usually between one and several hundred milliwatts per device, dependent on the function of the device and its design. Both ends of this power spectrum are being pushed by further research and development. For space research and other applications in which power is at a premium, devices that operate at microwatt power levels are needed. At the same time, attempts are being made to expand the high-power end of the spectrum because it is necessary to obtain enough power from silicon integrated devices to perform useful functions, specifically, for high-current monolithic voltage regulators. The upper limit is set by the ability of the package to remove heat from the integrated device. There is a high power level at which the utility of integrated devices is less than that of conventional component circuits. Thin-film circuits have the ability to operate at higher temperatures and thus have more efficient heat transfer for handling more power.

Some of the attributes of bipolar silicon integrated devices are listed in the following paragraphs:

1. *Batch Processing*. One important attribute of silicon integrated devices is that numerous devices are processed as a unit up to the stage where leads are attached and where the devices are encapsulated. This allows a high degree of process control and device uniformity, with relatively low unit cost.

2. *Processing Simplicity*. The number of processes involved in the fabrication of a silicon integrated device is very small when compared with the total number of separate processes required to fabricate the components of the conventional equivalent circuit.

3. *Device Diversity*. A single process can fabricate a variety of integrated devices by variation of the necessary photographic patterns.

4. *Materials*. In the silicon integrated device a small number of different materials are employed. For example, one class of devices employs silicon, silicon oxide, aluminum, and gold; no other materials are necessary. In the other types of integrated devices, additional materials may be employed. They may be other conductors or contacting materials or a resistive metal serving in thin-film resistors. Even with these, the number of different materials involved in the integrated device is small. This tends to promote high reliability.

5. *Area Factor.* The surface area of the single-crystal silicon die on which the integrated device is fabricated is very important. It influences yield and thus cost, allowable power dissipation, required quiescent power, package size, and functional capability. For a given structure, the present lower limit on area may be set by dissipation, current-carrying ability, capacitor and resistor parameters, or resolution limits of the photoengraving process. The latter is most important for low-power circuits, since for a fixed resolution the only trade-offs are between component tolerances and circuit size.

6. *Inverted Economics.* Because of the greater area required for capacitors and resistors on silicon integrated devices, these components add more cost to the integrated devices than do transistors or diodes. This is the reverse of the situation involving circuits designed with vacuum tubes or discrete transistors. The inversion of relative cost of the active and passive circuit components will continue to have significant impact on the design of ICs.

Table 1-1 compares bipolar IC with discrete circuits. Table 1-2 presents a comparative summary of the salient features of bipolar ICs, thin- and thick-film hybrid ICs, and metal–oxide–silicon (MOS) ICs.

Table 1-1 Comparison of Bipolar Integrated Circuits with Discrete Circuits

Bipolar ICs	Discrete Circuits
• Breakdown voltages BV_{BEO}: 5–8 V BV_{CBO}: 50 V	• Greatest design flexibility • Second sources are easy to obtain • Higher total systems cost
• Higher saturation voltage than discrete devices	
• High yield batch process	
• Lower power dissipation capability than discretes	• Capable of high power dissipation
• Limited component values	• Can obtain any desired component values
• Limited high-frequency capability	• Best high-frequency response
• Isolation between components required	• Individual components are isolated inherently by the spacing
• Lowest cost for both small and large quantities	
• Loose component tolerances	• Tight component tolerances
• High reliability	• Lower reliability
• Closely matched components	• Components not inherently matched
• Contains inherent parasitics	
• Available with both *pnp* and *npn* devices	• Available with both *pnp* and *npn* devices
• High initial design cost	• Low initial design cost
• Limited to low breakdown voltage	• High-breakdown-voltage transistors are readily available
• Not suited to very complex devices	
• Packaging complex devices present a problem	• Packaging is not a problem
• Not suited for many devices per chip	
• Use of inductance is prohibited	• All component types are available
• Small size and light weight	Large size and high weight

Table 1-1 Continued

Bipolar ICs	Discrete Circuits
• Highest tooling cost	
• Active substrate	
• Nonlinear capacitors	
• Best suited for large volume production where parasitics, component tolerances, and component temperature variations can be tolerated	
• Capacitor use should be minimized	
• Resistor values should be kept below 20 kΩ	• Any values of capacitors and resistors may be used
• Design should utilize active devices wherever possible	

Table 1-2 Comparison of Classes of Integrated Circuits

Bipolar ICs	Thin-film hybrid ICs
• High reliability	• Require more area than monolithic ICs
• Small and lightweight	• Can meet tighter specifications than thick-film ICs
• Good thermal coupling through substrate allows tracking with temperature	• Great design flexibility
• Highest tooling cost	• Larger and less reliable than monolithic ICs
• Lowest unit cost for both small and large quantities	• Greater power-handling capability than bipolar
• Typical temperature coefficient of resistance of 2000 ppm/°C	• Low-temperature die attachment
• Typical sheet resistance of 250 Ω/□	• High packing density of components due to fine line widths and conductor bar separation
• Active substrate	• Better stability, precision, temperature coefficient, drift, and noise than thick-film ICs
• Limited range of passive component values	• Must add discrete active elements to passive substrate
• Difficult to achieve close tolerances on passive components	• Second-highest tooling cost
• Limited high-frequency response due to parasitic elements	• Increase interconnections per chip
• Capacitors are nonlinear	• Highest unit cost for both small and large quantities
• Difficult to trim resistors to 1%	• Typical temperature coefficient of resistance: 50 ppm/°C
• Basic monolithic structures Epitaxial-diffused Diffused-collector Triple-diffused	