micro electronics

processing and device design

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Microelectronics: Processing and Device Design

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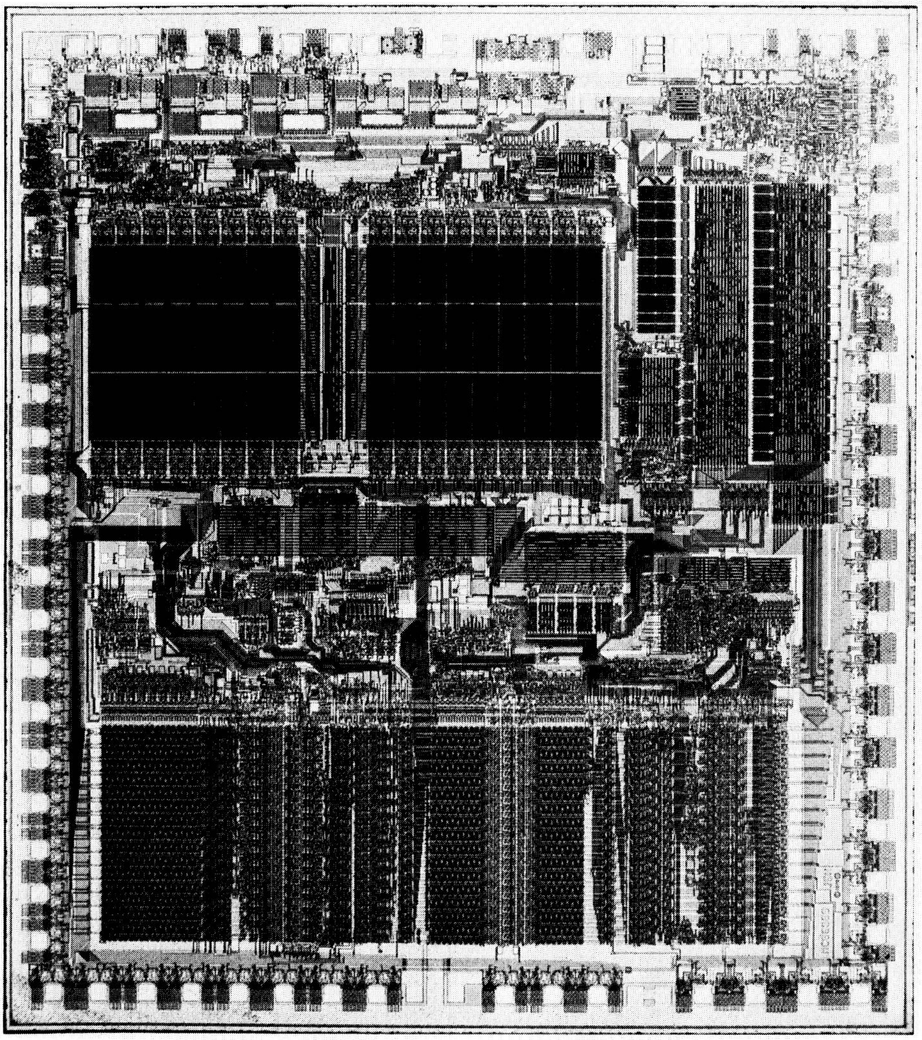

A large-scale integrated circuit, the MC68000 (Courtesy of Motorola, Inc., MOS Division).

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PREFACE

The world of microelectronics is characterized by technological advances that have occurred more rapidly than in almost any other field. During the 30 years since the discovery of the transistor effect, many processing techniques have been applied to the fabrication of microelectronic circuits. As I write this, new techniques continue to be tested, for example, laser assisted doping, which may or may not have a significant impact on future products. Each process imposes certain restrictions on the operating characteristics of the devices and components fabricated in part by the process. The purpose of this book is to investigate typical microelectronics processes and their influences on device design. It is anticipated that four basic technologies, thick-film hybrid, thin-film hybrid, monolithic bipolar, and monolithic metal-oxide-semiconductor (MOS), will each continue to dominate their share of the microelectronics market, based on their particular advantages for specific applications. For this reason, all four of these technologies are discussed, but the emphasis is on monolithic bipolar and MOS integrated-circuit processing and device design.

The material in this book was developed over a period of eight years while I was teaching lecture and laboratory courses on microelectronics at the senior and beginning graduate levels at The University of New Mexico. Valuable background information was also gained while I was on sabbatical and during summer employments with the Integrated Circuit Technology Division of Sandia Laboratories, Albuquerque.

It is assumed that the user of this book has a basic understanding of electronics and semiconductor materials at a level typical of students entering the senior year in an electrical engineering undergraduate degree program. In addition, students should be familiar with device physics at a level comparable to that of *Device Electronics for Integrated Circuits* by Muller and Kamins (Wiley, 1977). The appendix provides a brief introduction to (or review of) semiconductor materials and device physics. A complete background in the latter is not a necessity for using the results of Chapters 9 and 10, but the validity of many of the design equations must then be accepted by the reader.

The book is organized essentially into two parts, with Chapters 2 to 8 focusing on processing, and Chapters 9 to 11 concentrating on device and component design. As much as possible, the individual chapters are independent, and can be read in any order. The most notable exception to this is Chapter 7, "Selective Doping Techniques," which should be read before Chapter 9, "Devices for Bipolar Integrated Circuits." Problems are included at the ends of chapters where appropriate. The problems serve several purposes. Some of them are intended to clarify the text material and to make certain of the figures more meaningful. Others are numerical exercises that familiarize students with the appropriate orders of magnitudes to be expected for certain quantities. There are also some problems that are more challenging and will take more time and effort to complete. If a fabrication laboratory course accompanies the lecture, this text will provide informative background material to help in explaining why particular processes are performed as they are. Many of the graphs in the book are adapted from the literature in a new form which makes them more meaningful and relatively easy to use.

I am indebted to my students, who have been patient through three previous versions of the manuscript. Of particular inspiration were Bill Burnett, Fred Bird, and Mark McDermott. I also thank Donald Davis, Robert Kopp, Richard Muller, Jerry Sergent, Edward Graham, and Agustin Ochoa for their helpful suggestions after reading all or parts of the manuscript. I am indebted to The University of New Mexico for assistance in preparing the manuscript and to William R. Dawes, Jr., of Sandia Laboratories, Albuquerque, for providing the opportunity to work in a modern integrated-circuits fabrication facility. Finally, I am particularly grateful to Sharon Henze Burnett for typing the manuscript, to Robert Krein for assisting in the preparation of the figures, and to Gene Davenport, editor of electrical engineering and computer science at Wiley, for his advice and guidance.

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Chapter 1
An Overview of Microelectronics

The performance of information processing on a grand scale, either in analog or digital form, in almost zero space has been a goal, or dream, of mankind ever since the birth of electronics. Science fiction authors have casually assumed that scientists and engineers would eventually be able to produce marvelous devices like the two-way wrist television in *Dick Tracy** and the computers in Isaac Asimov's *The Last Question* (1), which increased in capability and decreased in size with each generation. Technological advances since the end of World War II have brought these dreams close to reality.

Microelectronics is that area of technology associated with the fabrication of electronic systems or subsystems using extremely small components. There are numerous ways to "shrink" electronic circuits. In this book, we will consider four technologies that are in widespread use for the manufacture of microcircuits.

Thick-Film Hybrid. Conductor, dielectric, and resistor patterns screen printed on ceramic substrates with "add-on" miniature components consisting of semiconductor devices and monolithic integrated circuits, capacitors, inductors, transformers, and so forth.

Thin-Film Hybrid. Conductor, dielectric, and resistor materials deposited by evaporation, sputtering, electro- or electroless plating on ceramic, glass, or crystalline substrates patterned by photoengraving or by depositing through a mask, with "add-on" components consisting of semiconductor devices and monolithic integrated circuits, capacitors, inductors, and so forth.

* *Dick Tracy* is a comic strip originated by Chester Gould and copyrighted by the Chicago Tribune.

Monolithic Bipolar. Bipolar junction and monopolar junction field-effect transistors, junction diodes, Schottky diodes, resistors, and capacitors formed by epitaxy, oxidation, ion-implantation, diffusion, chemical vapor deposition, and photoengraving on and within a single crystal semiconductor substrate and intraconnected by thin-film conductors.

Monolithic Metal-Oxide-Semiconductor (*MOS*). MOS field-effect transistors, capacitors, resistors, and conductors formed by oxidation, diffusion, ion-implantation, chemical vapor deposition, photoengraving, and thin-film deposition on and within a single crystal semiconductor or insulating substrate.

There are other possible ways for fabricating microcircuits, but most of these are based on combinations of the above technologies. Many of the terms listed above may be unfamiliar to the reader at this point, but they will be described in detail in subsequent chapters.

In this chapter, we will trace the origins of the four basic technologies and present examples demonstrating how each of the fabrication techniques could be applied to the fabrication of a microcircuit that will perform the same electronic function.

THE DEVELOPMENT OF MICROELECTRONICS TECHNOLOGY (2–6)

The first microcircuits in which components were integral with the substrates were developed by the Centralab Division of Globe-Union, Inc. in cooperation with the National Bureau of Standards. The circuits were subassemblies used in proximity fuses first employed during the Korean War. Development of these circuits started at the end of World War II. The early versions used conductors screen printed onto ceramic substrates with capacitors in chip form and miniature vacuum tubes as "add-on" components. Later developments included baked-on carbon resistors and high dielectric constant substrates which served as capacitor dielectrics. The development of resistor compositions that could be fired on the ceramic substrates was a major step in the development of thick-film hybrids.

The vacuum triode, and its refinements like the tetrode and the pentode, had served as the workhorse of the electronics industry for nearly half a century, when its worthy successor, the bipolar junction transistor was invented in 1948 by Shockley, Bardeen, and Brattain at Bell Laboratories, shortly after the invention of the point contact transistor. The vacuum tube suffered from high operating power dissipation, limited life expectancy, and fragile construction. The junction transistor had few such drawbacks, and immediately won acceptance as the best active component for many electronics applications. It should be noted that the operating characteristics of junction transistors, particularly in regard to input and output impedance levels, were significantly different from those of vacuum tubes, and brought about a change in the design philosophy necessary to accomplish specific electronic functions.

Nowhere was the transistor more welcome than in the emerging field of electronic data processing. The first large digital computers consumed as much power as a locomotive and often failed before the execution of even a short program could be completed.

The Bell Telephone System was interested in developing a highly reliable electronic switching system to replace their vast array of electromechanical relays. Vacuum tube switches were less reliable than relays, but the junction transistor outperformed both tubes and relays. As part of their new system, Bell adopted a new technology involving thin-film hybrid modules with resistors and capacitors designed to remain stable over periods in excess of 20 years. The close tolerances that could be maintained on a routine manufacturing basis using thin-film techniques resulted in a product superior to their previous efforts, at a lower cost. The small geometry components that could be obtained using these techniques resulted in circuits that could operate reliably at higher frequencies. The combination of thin-film technology and the junction transistor (and, later the monolithic integrated circuit) resulted in the improved electronic switching system so necessary for a modern telephone communications network.

The surface field-effect transistor (FET) had been proposed by Lilienfeld in 1926, but the first successful metal-oxide-semiconductor (MOS) FET was not fabricated until 1959 by Kahng and Atalla at Bell Telephone Laboratories. The major difficulties associated with the fabrication of these devices were related to the growth of ultraclean insulating layers.

Bipolar junction transistor technology had some significant developments during the 1950s. These advances set the stage for one of the most important inventions in the history of electronics, the monolithic integrated circuit. The early transistors were made from germanium, primarily by alloying or grown junction techniques. Germanium, plagued by operating temperature limitations due to its relatively small bandgap (0.7 eV compared to 1.1 eV for silicon), was gradually supplanted by silicon. One outstanding property of silicon is that it forms a stable oxide when exposed to oxidizing agents at high temperatures. This oxide provides a means of controlling the surface conditions of silicon, and acts as a protective "mask" so that impurities can be inserted by diffusion or ion-implantation into selected areas of the surface of the wafer from which the oxide has been stripped. These properties of silicon and its oxide plus developments in photolithography led to the invention of the planar bipolar transistor structure by Hoerni at Fairchild in 1958. The concept of the monolithic integrated circuit was first suggested by G. W. A. Dummer of the Royal Radar Establishment at the Electronic Components Conference in 1952. He said

With the advent of the transistor and the work in semiconductors generally, it seems now possible to envisage electronics equipment in a solid block with no connecting wires. (8)

There were a number of programs working toward this goal in the years to follow. The U.S. Army Signal Corps was sponsoring a program with RCA called the Micro-Module. The U.S. Air Force developed a program with Westinghouse called "molecular electronics," based on the concept of using the properties of materials to perform electronic functions. Wallmark and Nelson at RCA filed a patent in 1958 for a two-dimensional array of junction FET's isolated by reverse-biased *pn* junctions. Jack Kilby at Texas Instruments, who had previously worked at Centralab on thick-film hybrid circuits for hearing aids, invented what was eventually judged by the courts to be the first semiconductor integrated circuit. The circuit was an oscillator made in a single crystal germanium substrate with the components separated by mesa-etching and interconnected by wire bonding. This circuit was first fabricated successfully in 1958. Less than a year later, Robert Noyce at Fairchild brought together the developments of the previous 10 years. Using the planar process and junction isolation, the first integrated circuits, as we know them today, were fabricated.

The first commercial integrated circuits were introduced by Texas Instruments in 1960, and Fairchild's Micrologic® family appeared in 1961. These early circuits were mostly digital logic circuits which were readily accepted by the rapidly expanding computer industry.

One computer manufacturer, IBM, was planning the introduction of a new line of large computers for the mid-1960s. They did not feel that they were ready to commit themselves to the new technology for such a large project. Instead, they developed a manufacturing procedure using an automated technique for attaching special "flip-chip" transistors by means of solder bumps to thick-film substrates. This application demonstrated that thick-film hybrid technology could be used for mass production, since millions of these reliable circuits were produced. IBM called this "Solid Logic Technology." General Motors also made a high production commitment to thick-film hybrids for voltage regulators.

The success of the early digital bipolar integrated circuits provided the financial base for new, even more successful, logic circuits including the highly popular transistor-transistor logic (TTL) family. These digital circuits had almost universal appeal. The designers of analog integrated circuits were able to make use of the continued developments in technology to produce an outstanding circuit, the operational amplifier, which has become the cornerstone of the analog circuit market.

The MOSFET was not successfully fabricated until approximately the same time as the bipolar integrated circuit. It was natural for the MOS integrated circuit to develop during the same time period as that for the discrete MOSFET.

Since the introduction of the monolithic integrated circuit, there has been a continuing increase in the complexity of the circuits that could be economically fabricated on an individual chip. This has been accompanied by a gradual decrease in the minimum area occupied by typical components, due to advances in microphotolithography. Processing methods, device types, materials defects, and circuit design have been responsible for setting a limit on the die size that can be mass produced at any particular point in time. This limit is based on the ability to produce an "acceptable" yield of circuits which perform within the specifications that have been established for the particular design being implemented. Obviously, it is easier to produce saturating bipolar transistor logic circuits [which will accept a wide range of transistor common-emitter current gain (β)], and operate from a 3-V supply, than it is to produce an analog amplifier with a specific voltage gain intended to be operated from a 15-V supply. All of the devices and components within an individual circuit must function properly. A single defect, for example, a dislocation within the crystal structure occurring in an unfortunate location within a bipolar transistor, will render the entire circuit containing that transistor useless. The "acceptable" yield thus depends on the type of circuit being manufactured and the willingness of the users of these circuits to pay the premium required for a particular increment in the complexity of an electronic function. In other words, is the customer more willing to pay for a single circuit, with a smaller overall size and weight and increased reliability, than he would be for several circuits that could be interconnected to perform the same function? An increase in yield, to the point where the single monolithic circuit costs less than the individual circuits, naturally eliminates the need to even consider this question. From another viewpoint, making a single large circuit reduces the versatility available to the user of the individual circuits and introduces the concept of the custom integrated circuit as compared to the standard line or "family" of smaller individual circuits. The demand for the larger circuit must be great enough, or sufficiently "special," like a military or space application, to warrant production. It is clear that large volume products like automobile voltage regulators and hand-held calculators should be made from custom circuits, and that limited production items like implantable heart stimulators and geothermal instrumental probes should be made from standard product lines, but there are many applications in which the choice is not so obvious. The result of these varied demands from the market place has been the designation of several categories for standard monolithic integrated circuits according to size: small-scale integration (SSI), medium-scale integration (MSI), large-scale integration (LSI), and very large-scale integration (VLSI). These terms are usually restricted to digital circuits with the somewhat nebulous dividing lines associated with the number of logic gates per circuit.

The first attempts at LSI were intended to circumvent the gradual trends within the industry for increasing complexity and size based on refinements in processing techniques and materials development. This revolutionary approach was called discretionary wiring. An entire wafer (typically 2.5 cm in diameter) was to be used for a single circuit. An array of logic modules was fabricated within the wafer with test pads arranged so that each module could be individually probed and evaluated. A computer was used to determine which modules were useful, and how they could be interconnected to perform the overall task required of this gigantic circuit. Masks for multilayer interconnnection patterns were generated for each individual wafer. This was a technologically feasible method for achieving LSI, but it was an expensive technique. At the same time, MOS integrated circuit processing emerged from the development laboratory to take its place as a viable alternative to bipolar monolithic logic. Because of the higher component densities available in MOS circuitry, LSI could be achieved in circuits that were less than 1 cm on a side. LSI memory arrays, calculator chips, and digital watch circuits rapidly became commonplace. The long sought after "computer-on-a-chip," in the form of microprocessors, was soon to follow. As technology progressed, yields improved to the point that VLSI became possible in the form of 64-kilobit random access memories and charge coupled device imaging arrays capable of performing the functions of television cameras. Bipolar LSI, using a circuit design technique called integrated injection logic, has also emerged in the form of digital watch circuits and microprocessors. The development of submicrometer photolithography and new circuit concepts have enhanced the component density and circuit complexity to the point where VLSI circuitry occupies approximately the same area as previous LSI circuitry. The future of integrated circuit technology is exciting, to say the least.

Hybrid technology has also continued to develop at a rapid pace. Thin-film microwave and electro-optic circuits dominate the high frequency field. Surface-acoustic-wave devices employing thin-film patterns on piezoelectric crystals have been used to produce filter characteristics difficult to obtain by other techniques. A particularly important application of thick-film hybrids is the interconnection of LSI and VLSI chips into complex electronic systems by eliminating the large and expensive packages usually used for the individual chips.

In two decades, microelectronics has had a significant impact on the world. This far reaching impact has been due, in part, to the reduction in size and weight achieved by the shrinking of the apparatus required to perform electronic functions. Perhaps of even more importance than the changes due to size and weight have been the reduced cost, the increased performance, the reduced power consumption, and the increased reliability that have enabled microelectronics to displace numerous mechanical devices during this time period. Perhaps the most graphic example of this is in the field of digital computation. A microprocessor based digital computer system on a printed circuit board approximately 25 cm × 25 cm has more computing capacity than the first electronic computer, *ENIAC*. It is 20 times faster, has a larger memory, is thousands of times more reliable, consumes the power of a light bulb rather than that of a locomotive, occupies one-thirty thousandth of the volume, and costs one-ten thousandth as much (5). A hand-held calculator costing about one-half as much as an engineering-type slide rule is much more accurate, can perform many more functions, and even locates the decimal point for the user over a wide calculating range (typically 10^{-99} to nearly 10^{+100}). Some of the scientific programmable hand-held calculators have capabilities approaching those of the early computers. A "home" computer system, complete with video display, printer, "floppy-disk" storage, alpha-numeric keyboard, and high-level programming language costs less than an automobile. There are many other examples of the pervasive uses of microelectronics, too numerous to mention. The engineers involved with microelectronics are doing their part to make many of the authors of science fiction look like prophets.

A particularly interesting historical development and industry overview is given by Ernest Braun and Stuart MacDonald (7).

A COMPARISON OF MICROELECTRONICS TECHNOLOGIES

The four basic microelectronics technologies, thick-film hybrid, thin-film hybrid, bipolar monolithic, and MOS monolithic represent different approaches for producing circuits that will accomplish desired electronic functions. To make the optimum use of a particular technology, circuits should be designed to rely upon the unique capabilities of the fabrication technique which has been selected. To illustrate this concept, a basic electronic function, the logic inverter (NOT), has been selected to be implemented by each of the four technologies. These examples are not typical of contemporary microelectronics, but they will serve to introduce the reader to the processes and the design philosophies associated with the four technologies.

Thick-film hybrids are the largest of the microcircuits. A carefully designed thick-film hybrid microcircuit is somewhat less than one-half the size of a carefully designed printed circuit implementation of the same function. The components most readily fabricated by thick-film processes are resistors, and this technology provides the means for producing the widest range of resistor values which can be readily obtained in microelectronics, typically, any value between 0.1 Ω and 10 MΩ. Capacitors can also be fabricated using thick-film techniques, but it is common practice to use multilayer ceramic chip capacitors as add-on components, since they are smaller in size and have more reproducible characteristics. Conductor patterns and crossovers are readily produced in a thick-film production environment. Transistors, diodes, and integrated circuits are added to complete the process. These components can be attached to the circuit in standard packages, special packages, or configurations designed specifically for hybrids, or as bare chips. When necessary, miniature inductors and transformers can also be attached to the thick-film hybrid circuits. The designer of a thick-film hybrid microcircuit has essentially the same wide flexibility as that available to the designer of a discrete component electronic circuit.

The circuit selected to illustrate thick-film hybrid technology is shown in Figure 1-1. This is a diode-transistor logic inverter. The diodes and transistor will be attached in standard packages. The resistors and conductors will be printed on a ceramic substrate using thick-film inks. Resistors R_1 and R_2 will be printed using $1.0\ \text{k}\Omega/\square$ ink, and R_3 will be printed using $10.0\ \text{k}\Omega/\square$ ink. Thick-film resistors may be economically trimmed to $\pm 1\%$ of the specified value, if necessary.

The units associated with these inks, ohms per square ($\Omega/\square$), are units frequently encountered in microelectronics. They are derived from the following consideration. A film resistor is shown in Figure 1-2. The resistance of this structure is given by

$$R = \frac{\rho l}{tw} \tag{1-1}$$

where R is the resistance in ohms, ρ is the resistivity in ohms-centimeters, l is the length in centimeters, w is the width in centimeters, and t is the thickness in centimeters. Equation 1-1 can be rewritten in the form

$$R = R_S \frac{l}{w} \tag{1-2}$$

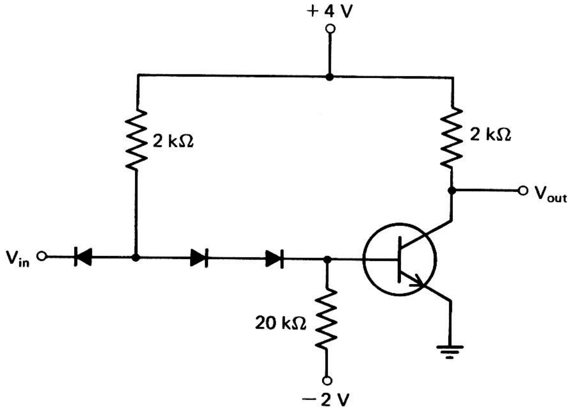

Figure 1-1. A diode-transistor logic (DTL) inverter.