MICROELECTRONICS

Digital and Analog
Circuits and Systems

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PREFACE

This book was written primarily as a text in modern electronics for electrical engineering students. Its comprehensive scope, in both breadth and depth, should also make it valuable to physics majors and to practicing engineers and scientists who wish to update their knowledge of the fast-changing field of microelectronics (integrated circuits).

The text is divided into three parts, thereby allowing it to be used in a number of different courses to suit the purpose and interest of the professor. Part 1 (Chapters 1–4) discusses *semiconductor device characteristics*, and is intended for students who have had no previous introduction to electronics. The physics and mathematics normally taught in the first year or two of an undergraduate curriculum are the only prerequisites required for an understanding of Part 1. These four chapters outline the properties of a semiconductor, explain fabrication of a *p-n* diode and a bipolar junction transistor (BJT) in monolithic integrated form, and include a discussion of their characteristics. Discrete devices no longer play such an important part in the design of today's electronic products, and hence the reader is introduced to the integrated circuit (IC) chip early in the book (Chapter 4).

Part 2 (Chapters 5 through 9) explores *digital circuits and systems*. There are a number of important reasons for introducing digital material before analog material:

1. Digital techniques, which involve only simple Boolean algebra, are easily learned by the student. The devices are either ON or OFF, resulting in very simple operation. Essentially the only characteristics that need be specified are switching speed and the loading on a gate. Analog considerations, on the other hand, are much more difficult to grasp since they involve frequency- and time-domain concepts, frequency compensation, and more detailed and complicated circuit analysis. Many small-signal-device parameters must be taken into consideration.

Part 2 requires no electrical engineering prerequisites since the very simple circuit analysis needed for digital networks is explained in Appendix C, Summary of Network Theory. Hence, a course covering *digital electronics* could be made available to sophomores.

2. Most students have learned how to program the digital computer (some learned in high school). Hence a very strong motivation for them to study electronics is to find out how digital hardware works.
3. In many universities (Columbia is one of them), only a one-semester electronics course is required for the computer science option in electrical engineering. Clearly, the scope should concentrate on digital electronics, and such a course can use Parts 1 and 2 for its text. These nine chapters contain somewhat more material than can be covered in one semester, which gives the instructor the freedom to omit those sections he or she feels are of less interest or importance.
4. Most electronics curriculum requirements include laboratory work. It is much simpler to design and perform digital, rather than analog, experiments. Such a laboratory course may be a corequisite for the digital course. This arrangement is not too successful with an analog laboratory because network theory courses are required as prerequisites.
5. Most new electronic systems are predominantly digital in nature.

Part 2 introduces small-scale integration (SSI) logic gates (AND, OR, NOT, NAND, . . .), and these are implemented into the various standard families (DTL, TTL, ECL, . . .). Then follows combinational systems, which are medium-scale integration (MSI), such as a binary adder, a digital comparator, a parity checker, a decoder/demultiplexer, a data selector/multiplexer, an encoder, and a read-only memory (ROM). As examples of sequential digital systems we consider FLIP-FLOPS (*S-R*, *J-K*, *T*, and *D* types) and use them as the building blocks for shift registers and counters.

Now that the student has gained some facility in the use of the bipolar transistor and has seen its application to digital systems, a new semiconductor device, the field-effect transistor, is introduced and exploited in logic gates. Finally, large-scale integration (LSI) systems with both MOSFETs and BJTs are studied in Chapter 9. These are principally memories and include dynamic MOS shift registers, MOS ROMs, erasable programmable read-only memories (EPROMs), programmable logic arrays (PLAs), random-access memories (RAMs), charge-coupled devices (CCDs), the microprocessor and microcomputer, and integrated-injection logic (I^2L).

Part 3 (Chapters 10 through 18) concentrates on *analog circuits and systems*. Methods of biasing a discrete BJT or FET are given, and stability of the operating point is discussed. The small-signal model for each device is obtained and used to calculate the performance of low-frequency single-stage and cascaded amplifiers.

Feedback concepts are introduced. The four standard feedback amplifier configurations are indicated and their characteristics are delineated. High-frequency transistor models are used to obtain the frequency response of amplifiers (with or without feedback).

The basic linear (analog) building block is the operational amplifier (OP AMP), and its characteristics and applications are described in the last four chapters. Monolithic analog design techniques for the OP AMP are presented in detail, including methods of frequency compensation to assure stability. The broad applications of OP AMPS which are discussed include: instrumentation amplifiers, analog computers, active filters, precision AC/DC converters, sample-and-hold systems, analog multiplexers and demultiplexers, logarithmic amplifiers, D/A and A/D converters, comparators, waveform generators, voltage time-base generators, sinusoidal oscillators, power amplifiers, and monolithic voltage regulators.

For a two-term electronics sequence, the second course would be based on Part 3. This material is too extensive for one course, which allows the professor the option of selecting those topics he or she wishes to emphasize.

Many curricula require only one *core* course in electronics, but then offer a number of optional electronics courses. This book contains enough material for a total of 3 one-semester courses.

If a professor wishes to consider analog material before digital material in a first electronics course, then Part 1 and selected portions of Part 3 could be used. However, Sections 8-1 through 8-6 of Part 2 on field-effect transistors should be included.

From the foregoing discussion it should be clear that the various topics in this book have been written in such a manner as to allow great latitude in the structuring of one or more courses, the content of which matches that desired by the instructor.

The number of components on a chip has doubled every year since 1959 when the planar transistor was introduced. With this ever-increasing component density on an IC chip the difference between an electronic circuit and a system becomes quite blurred. As a matter of fact an entire monolithic package, such as an OP AMP, is often referred to simply as a "device." In this book no attempt is made to distinguish unambiguously between *device*, *circuit*, or *system*; although, of course, a single transistor is clearly a device and a large-scale microelectronic chip merits the designation "system" or at least "subsystem."

Modern electronics engineers design a new product (for example, an instrument, a control, computer, or communication system, etc.) by interconnecting standard microelectronic chips so that the overall assembly will achieve the desired external objectives. They try to minimize the number of packages (and, hence, the cost) by using LSI and MSI wherever possible, and they only resort to SSI chips and discrete components (such as very large capacitors or resistors, inductors, transformers, transducers, etc.) whenever absolutely necessary. Clearly, engineers must know what IC chips are commercially available, what functions they perform, and their limitations.

In view of the foregoing facts the goal of this book is to take the reader step by step from a qualitative knowledge of the properties of a semiconductor to an understanding of the operation of devices (particularly the *p-n* diode, the BJT, the MOSFET, the CCD, and the I^2L gate), and finally to an appreciation for how these are combined monolithically to form microelectronic chips with distinct and useful input-output properties. A very broad variety of IC chips are studied in this book, including not only a description of what is fabricated within the silicon but also a deep understanding of the digital and/or analog functions which this chip can perform. After each circuit or system is studied, reference is made to a specific commercially available package which can give the desired operation (for example, digital multiplexing, analog comparison, digital-to-analog conversion, etc.). The practical limitations (due to temperature, voltage, power, loading, etc.) of real, rather than idealized, devices are explained. To appreciate these nonideal characteristics, manufacturer's specifications for representative discrete devices and IC chips are supplied (Appendix B). The depth of discussion, the broad choice of topics, and the practical emphasis is such as to prepare the student to do useful engineering immediately after he or she joins an electronics company.

This book is a thorough reorganization, rewriting, and updating of the material in Millman and Halkias "Integrated Electronics: Analog and Digital Circuits and Systems" (McGraw-Hill Book Company, New York, 1972). Many new topics have been added, including but not limited to the following: three-state output stage of a logic gate, higher-order demultiplexer and multiplexer, priority encoder, two-dimensional addressing of a ROM, word and address expansions of ROMs, a universal shift register, technological improvements in MOSFETs, inverters with nonsaturated or depletion loads, CMOS transmission gates, erasable programmable ROM, programmable logic array (PLA), dynamic RAM cells, charge-coupled devices (CCD), microprocessor, integrated-injection logic (I^2L), analog design techniques (current sources and repeaters, active load, level-shifting, and output stage of an OP AMP), sample-and-hold systems, analog multiplexer and demultiplexer, several A/D converter systems, voltage-controlled oscillator, positive-negative controlled-gain amplifier, retriggerable monostable multivibrator, voltage time-base generators, modulation of a square wave, power amplifiers (including thermal considerations), switching-regulated power supplies, and power FETs (VMOS). An attempt was made to present the state of the art of microelectronics as of early 1978 and to indicate some probable future developments.

To make room for the new material, some of the topics in "Integrated Electronics" were compressed or omitted completely. For example, the discussions of semiconductor device physics were drastically reduced, the biasing of discrete devices was deemphasized, the photoelectric effect in a semiconductor was deleted, the four-parameter low-frequency hybrid model was mentioned only briefly, and the discussions of amplifier noise, of tuned amplifiers, and of CRT character generators were omitted.

A brief historical survey of electronics and electronic industries is included in the Prologue (following this preface). It is hoped that the instructor and the student will read this fascinating history before beginning the study of the text.

Considerable thought was given to the pedagogy of presentation, to the explanation of device-circuit-system behavior, to the use of a consistent system of notation, to the care with which diagrams were drawn, to the illustrative examples worked out in detail in the text, and to the review questions at the end of each chapter. These review questions should be assigned as homework since they afford the students the opportunity to test themselves to see if they understand what they have read in the sections under consideration. The author has used these questions very successfully for about 30 percent of a quiz or an exam (the remaining 70 percent being quantitative problems).

Included are 717 homework problems, which will test the students' grasp of the fundamental concepts enunciated in the book and will give them experience in the analysis and design of electronic circuits and systems. In almost all numerical problems realistic parameter values and specifications have been chosen. Only a small percentage of the homework exercises are taken intact from "Integrated Electronics." Most of the problems are new or are modifications of those previously used. The answers to selected problems are found in Appendix E.

A solutions manual is available to an instructor who has adopted this text. Write to: College Division, McGraw-Hill Book Company, 1221 Avenue of the Americas, New York, NY 10020. Attention: Electrical Engineering Editor, 27th floor. As an added pedagogical aid, a set of 124 involved figures in the book are also available to the instructor. These may be used with a view graph during lectures on this subject matter.

The publishers sent a questionnaire to many of the professors who had adopted "Integrated Electronics," asking for desirable deletions, additions, revisions, etc., in this book. The present text reflects the replies to this questionnaire. I am especially grateful to Professor J. E. Steelman for his many helpful suggestions. Let me state specifically that the approach used in Section 13-3 follows notes which he sent to me. It is with great pleasure that I acknowledge the technical consultations and assistance of my son, Dr. J. T. Millman. In particular, he is responsible for the revision of Chapter 18. I also wish to express my great appreciation to Professor D. A. Hodges for his detailed review and very constructive criticism of Chapter 9. My thanks goes to Dr. T. V. Papathomas who was responsible for the preparation of the "Solutions Manual," and to Mrs. B. Lim for her skillful typing of the manuscript and the problem solutions.

Jacob Millman

PROLOGUE

A BRIEF HISTORY OF ELECTRONICS

This prologue to the text gives a historical perspective of the development of electronic devices which operate at frequencies from dc to hundreds of megahertz. It also includes a discussion of the growth of industries resulting from the exploitation of these devices into practical circuits and systems.

BACKGROUND

"Electronics" has different meanings to different people and in different countries. Hence, let me define the term in the sense that it is used here. "*Electronics* is the science and the technology of the passage of charged particles in a gas, in a vacuum, or in a semiconductor." Please note that particle motion confined within a metal only is not considered electronics.

Before *electronic engineering* came into existence, *electrical engineering* already flourished. Electrical engineering is the field which deals with devices that depend solely on the motion of electrons in metals; for example, a generator, a motor, a light bulb, or a telephone. The principal benefactors of these devices are the wire telephone or telegraph companies and the power industries.

Both electronic and electrical engineering owe their existence to the pioneering work in electricity and magnetism of scientific giants such as Coulomb, Ampere, Ohm, Gauss, Faraday, Henry, and Maxwell. Maxwell, in about 1865, put together the researches of the others into a consistent theory of electromagnetism, now called *Maxwell's equations*. Here is a historical example of theory being ahead of experiment, for although Maxwell's theory predicted that electromagnetic waves could be propagated in space and that light was such an electromagnetic wave, it was not until 23 years later (in 1888) that Hertz produced such radiation, using a spark-gap oscillator. In 1896 Marconi succeeded in transmitting Hertzian waves and detecting them at a distance of about two miles. Wireless telegraphy had its feeble origin in this experiment.

This history is divided into two periods of time, referred to simply as the *past* and *present*. By *past* is meant the era of the tube—the vacuum tube or the gas tube. The *present* starts with the invention of the transistors in 1948. Also included is a section speculating briefly on the *future*.

THE PAST

The beginning of electronics came in 1895 when H. A. Lorentz postulated the existence of discrete charges called *electrons*. Two years later J. J. Thompson found these electrons experimentally. In the same year (1897) Braun built what was probably the first electron tube, essentially a primitive cathode-ray tube.

Discovery of Vacuum Tubes

It was not until the start of the 20th century that electronics began to take technological shape. In 1904 Fleming invented the diode which he called a *valve*. It consisted of a heated wire which emitted electrons separated a short distance from a plate in a vacuum. For a positive voltage applied to the plate electrons were collected, whereas for a negative potential the current was reduced to zero. This valve was used as a detector of wireless signals. Two years later, Pickard tried a silicon crystal with a cat's whisker (a pointed wire pressed into silicon) as a detector. This was the first semiconductor diode. This device was very unreliable, was soon abandoned, and semiconductor electronics died a premature death in 1906.

The most important milestone in this early history of electronics came in the same year (1906) when De Forest put a third electrode (a grid) into the Fleming valve, and thus invented the triode tube which he called an *audion*. A small change in grid voltage resulted in a large plate-voltage change. Hence, the audion was the first amplifier. It took about five years to improve the vacuum in the audion and to add an efficient oxide-coated cathode in order to obtain a reliable electronic device. Thus the age of practical electronics began in about 1911. (By coincidence, I was born in the same year.)

Radio and Television

The first application of electronics was to radio and, simultaneously with the birth of electronics, the IRE (the Institute of Radio Engineers) was founded in the United States in 1912. It is a great tribute to the imagination of the early engineers that they realized immediately the importance of radio and formed this organization at the very beginning of radio communications. The American Institute of Electrical Engineers, which took care of the interest of conventional electrical engineers, had already been founded in 1884. Both societies combined in 1963 to become the IEEE (the Institute of Electrical and Electronic Engineers).

The first radio broadcasting station, KDKA, was built in 1920 by Westinghouse Electric Corporation in Pittsburgh, Pennsylvania. By 1924, just four short years later, there were 500 radio stations in the United States. The history of broadcasting (both radio and TV communications) can be divided into three main periods.

1907 to 1927 The devices available were simply diodes and triodes with filamentary-type cathodes. The circuits that were invented by the ingenuity of the engineers were cascaded amplifiers, regenerative amplifiers (Armstrong† in 1912), oscillators, heterodyning (Armstrong in 1917), and neutralization to prevent undesired oscillation in amplifiers.

1927 to 1936 The indirectly heated cathode was invented for the diode and triode. Two additional electrodes—a fourth and then a fifth—were introduced into the triode to form the screen-grid tube and the pentode, respectively. Also beam-power tubes and metal tubes were introduced during this period. With these new devices, engineers were able to invent the superheterodyne receiver, automatic gain control (AGC), single-knob tuning, and multiband operation. Radio was a flourishing business.

1936 to 1960 In this last period the new devices were closely spaced electrodes (for a high gain-bandwidth product), miniature glass tubes, and, toward the end of the period, color television tubes. Major Armstrong in 1933 invented frequency modulation. About five years later the first FM receiver was available. Electronic black and white television began in about 1930, and the most important name here is Zworykin of RCA. Ten years later, television, at least in the United States, was in fair use.

Commercial color television began around 1950, and many new functions had to be performed. Hence, the following circuits were invented: FM limiter, FM discriminator, automatic frequency control (AFC), saw-tooth waveform generator (linear deflection for a TV tube), synchronization, multiplexing, and inverse-feedback circuits (including operational amplifiers).

Electronic Industries

These can fit into one or more of the following four principal groups, which I shall call the four *C*'s: *C* for *C*omponents, *C* for *C*ommunications, *C* for *C*ontrol (or automation), and *C* for *C*omputation. The components companies up to this time were those which came into existence to supply the various types

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† Armstrong was an undergraduate at Columbia University at this time.

of tubes just described and others referred to later as well as the passive-circuit elements, such as resistors, capacitors, coils, transformers, etc.

The second *C* (communications) refers to the industry built up around AM and FM radio, hi-fi systems, and black and white as well as color TV receivers and transmitters.

The third *C* introduced (the *C* for control) was making itself evident in what was then referred to as "industrial electronics." Industrial electronics may be defined as "the use of electronic devices in the control and operation of machines in industry (other than in communication and computation)." The devices for industrial electronics were gaseous diodes and triodes (thyratrons), pool-cathode devices, such as the Mercury arc rectifier, and high-voltage and high-power tubes. The circuits for this period were power rectifiers, high-voltage rectifiers, power amplifiers, high-voltage transmitting circuits, induction and dielectric heating, power inverters (from dc to ac), measurements, motor control, and the control of industrial processes.

The computer (the fourth *C*) had barely made its appearance at this time and, hence, this industry is discussed in detail in the following.

THE PRESENT

This era begins with the invention of the transistor about 30 years ago.

Discovery of the Bipolar Junction Transistor

The history of this invention is interesting. M. J. Kelly, director of research (and later president of Bell Laboratories), had the foresight to realize that the telephone system needed electronic switching and better amplifiers. Vacuum tubes were not very reliable, principally because they generated a great deal of heat even when they were not being used, and, particularly, because filaments burned out and the tubes had to be replaced. In 1945 a solid-state physics group was formed. The following quote is from the authorization for work for this group: "The research carried out in this case has as its purpose the obtaining of new knowledge that can be used in the development of completely new and improved components and apparatus elements of communication systems." One of the most important specific goals was to try to develop a solid-state amplifier. The group consisted of theoretical and experimental physicists, a physical chemist, and an electronics engineer, and they collaborated with the metallurgists in the laboratory. These scientists were well aware of the theoretical research on metals and semiconductors already carried out by Block, Mott, Schottky, Slater, Sommerfeld, Van Vleck, Wigner, Wilson, and other physicists throughout the world. (I had the good fortune of doing graduate work under two of these professors, Sommerfeld and Slater.)

During an experiment in December 1947, two closely spaced gold-wire probes were pressed into the surface of a germanium crystal. It was found that the voltage output (with respect to the germanium base) at the "collector" probe was greater than the input to the "emitter" probe. Brattain and Bardeen immediately recognized that this was the effect they were looking for, and the solid-state amplifier (in the form of the point-contact transistor) was born. These first transistors were very bad. They had low gain and a low bandwidth and were noisy. Also, the parameters varied widely from device to device.

Shockley recognized that the difficulties were with the metallic point contacts. He proposed the junction transistor (Chapter 3) almost immediately and worked out the theory of its operation. Here was a device that had no pointed wire contacts and the transistor operation depended on diffusion instead of on the conduction current which was present in a tube. The new devices had charge carriers of both polarities operating simultaneously; they were bipolar devices. The carriers were electrons, which were well known, and other "strange particles" which were not well understood. Measurement showed their polarity to be opposite to that of the electrons, and hence they were equivalent to positive charges. These particles could only be explained with quantum-mechanical theory. They were called "holes" because they represented places in the crystal where electrons should have been but were missing. The current in a vacuum tube is limited by an electronic space charge built up in the vicinity of the thermionic emitter. This space charge, this cloud of electrons, repels any further electrons from being emitted. This phenomenon could not be present in a transistor because the theory predicted that the new device would be essentially neutral except for a thin, immobile space-charge layer close to a junction. Hence very large current densities could be expected from these new devices at low applied potentials. The possibility of obtaining important practical devices (*without heated filaments*) was immediately recognized.

From theoretical considerations it was known that the transistor could not be built reliably unless ultrapure single crystals were available. About two years later, Teal of Bell Labs grew single crystals of germanium and later silicon with much less than one part in a billion of impurity atoms. It was then possible to intentionally introduce controlled impurities called *donor* or *acceptor* atoms the extent of only one part in 100 millions. In this way they formed the junctions (Section 2-1) of the bipolar transistor. The first grown junction transistors appeared in 1950. The alloy junction process appeared the next year. Three short years after the discovery of amplification in a solid, the transistor was being produced commercially in 1951.

The Bell System made a most important corporate decision—not to keep these discoveries secret. It actually held symposia to share this knowledge with professors (who then could pass it on to students), and even with other companies. It offered to license its patents to any company that was interested in fabricating transistors. The tube companies such as Western Electric (which does the manufacturing for the Bell System), RCA, Westinghouse, and General Electric were the first to fabricate transistors, to be followed by many new components companies that saw the tremendous possibilities of this device. A current list of semiconductor device manufacturers is given in Appendix B-1.

By 1952, United States military funds were allotted to transistor research. The Armed Services was interested in using these devices mainly in missiles where small size and weight, low power, improved performance, and reliability (because of the absence of a filament) were of primary importance. This investment paid off very well. Solid-state components have virtually replaced tubes in almost all military and also commercial applications, except those involving exceedingly high voltage and power. Most universities in the United States no longer even mention the vacuum tube in their curricula.

Transistor characteristics vary greatly with changes in temperature. For germanium these variations become excessive for temperatures higher than about 75°C, whereas silicon can be used up to approximately 200°C. In 1954 production of the silicon transistor was announced by Texas Instruments. Today the vast majority of semiconductor transistors and other devices are fabricated from silicon.

In 1956 Bardeen, Brattain, and Shockley received the Nobel prize in physics. This was the first Nobel award ever given for the invention of an engineering device.

The Integrated Circuit

Shortly after joining Texas Instruments in 1958 Kilby conceived the monolithic idea, that is, the concept of building an entire circuit out of germanium or silicon. He used the bulk semiconductor to form a resistor, and he also fabricated a diffused-layer resistor (Section 4-9). He built a capacitor by using an oxide layer (for the dielectric) on silicon, and he also thought of the *p-n* junction capacitor (Section 4-10). To demonstrate the feasibility of his concept, he built a phase-shift oscillator and then a multivibrator using these resistors, capacitors, and a transistor, all made from germanium with thermally bonded gold connecting wires. However, in the patent application, he indicated that the components could be interconnected by laying down conducting material. In 1959 the *solid circuit* (later called the *integrated circuit*) was announced by Kilby at an IRE convention.

About this same time Noyce, then director of research and development at Fairchild Semiconductor (and now chairman of the board of Intel), also had the monolithic-circuit idea for making "multiple devices on a single piece of silicon in order to be able to make interconnections between devices as part of the manufacturing process, and thus reduce size, weight, etc., as well as cost per active element." He explained how devices could be isolated from one another with back-biased *p-n* diodes, how resistors could be fabricated, and how connections could be made by evaporating metal through holes in the oxide to interconnect the circuit components. (The idea of using back-to-back diodes for isolation of components was conceived independently and patented in 1959 by Lehovec, the research director of Sprague Electric Company). The first modern diffused transistors (Chapter 4) were developed by Hoerni at Fairchild in 1958. He was responsible for the planar process of passivating the junctions with an oxide layer on the surface. He used production photolithographic techniques and diffusion processes previously developed by Noyce and Moore. The real key to integrated-circuit manufacturing was the planar transistor and batch processing. By 1961, both Fairchild and Texas Instruments were producing integrated circuits commercially, and other companies soon joined them in IC fabrication. Today millions of transistors, passive components, and their interconnections are manufactured simultaneously (Chapter 4) in one production batch.

Field-Effect Transistors

Before the invention of the transistor a number of people studied the "field effect," that is, the change in conductivity of a solid caused by an applied transverse electric field. In fact, the bipolar transistor was discovered, as noted in the foregoing, during these field-effect investigations. The junction field-effect transistor was proposed by Shockley in 1951. However, early attempts to fabricate these devices failed because a stable surface could not be obtained. This difficulty was overcome with the discovery of the planar process and the surface passivation with silicon dioxide (glass, an excellent insulator). A metallic electrode (the *gate*) was placed over this thin (1,000 Å) SiO_2 layer. A voltage applied between the gate and the bulk silicon induced conductive charges near the surface. The gate extended laterally a few micrometers (referred to as the *channel*) between two electrodes (called the *source* S and *drain* D) and the current between S and D was controlled by the gate voltage. The first such metal-oxide semiconductor field-effect transistor (MOSFET, Chapter 8) was announced by Kahng and Atalla of Bell Laboratories in 1960. The reproducibility of these devices was poor. It took about five years to trace the difficulty to contaminants (principally sodium ions) in the SiO_2 and to learn how to eliminate them. Many technological improvements (Section 8-6) have been made in the basic MOSFET and this device now rivals the bipolar transistor in importance.

Charge-Coupled Device

It is possible to fabricate a long chain of closely spaced gate electrodes between S and D. Charge introduced from S can then be trapped under the first electrode and, by applying the proper voltage waveforms, this charge can be moved from the first to the second, and then from the second to the third electrode, etc. This so-called *charge-coupled device* (CCD) was invented by Boyle and Smith at Bell Laboratories in 1969 (Section 9-8).

Microelectronics

Reliability, speed of operation, and production yields have steadily improved, while cost, power consumption, and size have been reduced drastically for both bipolar junction transistor and MOSFET integrated circuits. The following approximate dates give some idea of the increase in the component (transistor, diode, resistor, or capacitor) count per IC silicon chip:

1951—*discrete transistors*
1960—*small-scale integration* (SSI), less than 100 components per chip
1966—*medium-scale integration* (MSI), more than 100 but less than 1,000 components per chip
1969—*large-scale integration* (LSI), more than 1,000 but less than 10,000 components per chip
1975—*very-large-scale integration* (VLSI), more than 10,000 components per chip

Moore, president of Intel, noted in 1964 (when he was director of research at Fairchild) that the number of components on a chip had doubled every year since 1959, when the planar transistor was introduced. He predicted correctly that this trend would continue. The size of a large silicon IC chip is only about 3 by 5 mm in area and only about 0.1 mm thick (about the thickness of one hair on your head). This chip might contain (in 1978) some 30,000 components, corresponding to 2,000 components/mm^2 or about 1 component/mil^2. These numbers are difficult to believe when one first learns of them, particularly since the IC's are manufactured in an industrial plant and not under research conditions in a laboratory. The term *microelectronics* is used to describe such high-density IC chips. There is now commercially available an entire computer on a single chip the area of which is about 6 by 6 mm. This microcomputer (Section 9-11) is a complete general-purpose digital-processing and control system and indicates what has been attained in (VLSI) microelectronics by 1977. In that year most of the world's $90 billion electronics industry depended on microelectronics.

The first IC's were digital logic circuits (Chapter 5), and these gates were interconnected to form combinational systems (Chapter 6), and sequential systems (Chapter 7). Starting in 1964, linear integrated circuits (Chapter 15) became available, and analog IC systems (Chapters 16 and 17) have flourished.

Semiconductor Memories

A number of transistor configurations have been devised for storing digital data. These are called *random access memories* (RAMs, Section 9-6), and the first LSI RAMs were sold commercially in 1970 by Intel and Fairchild. These early RAMs stored (approximately) 1,000 binary bits of information. By 1973 16,000-bit memories were introduced by Intel and Mostek, and 65,000-bit RAMs are expected to be commercially available in 1979. The CCD can be used as a circulating memory, and in 1977 65,000-bit CCDs were produced.

Integrated Injector Logic (I^{2}L)

Until recently the MOSFET occupied a very much smaller area than the BJT, but the latter was much faster than the former. In 1972 this situation changed when Berger and Wiedman at IBM (Germany) and Hart and Slob at Philips (Netherlands) invented a new bipolar transistor logic gate, called *integrated-injection logic* I^2L, Section 9-12. This is not a new device, but rather a new circuit configuration which uses standard BJT fabrication technology. The density of I^2L gates has increased to that of MOSFET gates, the speed is high, and the power is low. In 1977 Texas Instruments and Fairchild Semiconductor introduced I^2L chips commercially, and this logic is appearing in digital wrist watches, memories, and microprocessors. Technological improvements are now taking place in MOSFETs, which are increasing their density on a chip and increasing their speed. Hence, it is not evident that there will be a clear-cut victory of the I^2L over the MOSFET, or vice versa.

Communications and Control Industries

These industries adopted solid-state electronics, slowly at first, but now almost all equipment is transistorized, except those involving extremely high voltage or power. For medium voltage or power, discrete transistors are used. Such application of discrete transistors includes power switches (for paper punches or tape drives), motor controls, automobile ignition systems, TV deflection circuits, inverters, power supplies, and audio and radio-frequency output stages. For most other applications, the IC has taken over.

The communication industry has changed drastically because of microelectronics. In 1970 the transmission of data constituted a very small fraction of the volume of messages. In 1980 digital transmission is expected to equal voice (analog) transmission. Switching and memory in telephone systems are now performed by digital microelectronics. Active voice-frequency filters, which are analog, are also implemented with IC's. Obviously, communication satellites became feasible and economically viable because of microelectronics.

Similarly, the control industry has been affected drastically by microelectronics. Instrumentation, testing, automation of production processes, numerical control of machine tools, and energy management are predominantly digital- and computer-controlled, made possible because of integrated circuits.

The Computer Industry

The most dramatic outgrowth of the microelectronic revolution, however, was the creation of an entirely new industry—the computer industry. There has been a great deal of interest in computing machines for over 300 years. For example, in 1633 Schickhard in Germany described (in correspondence with his friend Kepler, the astronomer) a mechanical computer to do addition, subtraction, multiplication, and division. He designed a wheel with ten spokes on it, one spoke of which was longer than the others, and this wheel was placed mechanically next to another similar wheel. After the first wheel made ten angular increments, which corresponded to the ten digits, the large spoke engaged the next wheel, and it would turn one increment. In other words, he invented the