SEMICONDUCTOR ELECTRONICS DESIGN

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Preface

This is more than just a revision of a somewhat out-of-date text. In the eight years since its publication, the solid state electronics revolution *has* arrived. The integrated circuit, in its MSI and LSI forms, has made memory, logic, even complete calculators and computer microprocessors for military and consumer electronics available on a single chip of silicon. The original book, *Modern Transistor Electronics Analysis and Design*, which had called these circuits SIC's (Silicon Integrated Circuit) was then very up-to-date and even today still contains completely valid material. The processing procedure is essentially unchanged but has become much more technologically advanced. However, we have gone so far from there in reducing costs, increasing yields, shrinking size, reducing power consumption, and increasing complexity of functions and component densities that extensive new material and several chapters had to be added to the text. We do this at peril, however, since the acceleration of progress in the field is so rapid that even what we write today may be superceded by the time you read this book and thus require another extensive revision.

However, it should be made clear that the fundamental premises have not changed so that what has occurred to permit cheap and reliable electronic watches, calculators, radios, color televisions, automobile ignitions as well as automatic braking and anti-skidding computer systems, etc. can still be understood on a component function basis. That is to say, it is just as important today to know how a simple bipolar transistor amplifier operates, is biased, and has temperature and frequency limitations as it was ten years ago; this is so since each IC chip merely reflects the interconnection and assembly of large numbers of these discrete components in a more cost effective and space saving arrangement.

Changes have therefore been made in each chapter to reflect what has occurred in the last decade. New devices, such as the MOSFET, LED, and CCD are described as well as new logic arrangements such as T^2L and I^2L. The integrated operational amplifier or op-amp has such wide applicability that an entirely new chapter has been added on its operation and use in circuits. Extensive new material has been included on complete circuits and systems. An example which illustrates this involves complete modulator and demodulator functions on a chip, which now make modems and other communication circuits small and cheap. Along with coders and decoders for BCD and ASCII, these all permit, with microprocessor and memory chips, a complete 4 or 8 Kbit minicomputer to fit on one small PC card. Semiconductor memories such as RAM, ROM, PROM, etc., made on a single chip form MOS or bipolar transistors, are also described, since most new electronic systems now incroporate some memory in them.

The recent advances in device physics are introducing solid state electronics to new areas. No longer is the designer confronted only with p-n junction diodes and pnp or npn transistors (along with passive elements) for solving electronic circuit design problems. He must now be capable of designing a complete circuit on a monolithic substrate the size of the head of a pin. Thus, circuit design in many areas, especially that of digital circuits for use in computers, now entails putting together many such microcircuits into a subsystem and many of these subsystems into a complete system. The circuit designer must therefore become systems-oriented, and the scope of his task is correspondingly widened.

Since, in digital circuits, the microcircuit rather than the device is the fundamental building block, one might feel that the ability of a design engineer to develop the circuit might be less important than the ability to put the circuits together into a system. Considerations such as tolerances with respect to temperature, bias, humidity, vibration, etc., are even more important in the proper operating characteristics of the device and circuit than in conventional design since mass production and linking of these subassemblies into a working system are essential. Thus, an elementary understanding of the limitations of the basic amplifying device and of the fundamental circuit building blocks is not only essential but crucial to the entire field. Ground plane problems, shielding to reduce interaction between circuits, power-supply filtering to reduce unwanted mixing of signals, tolerances on components, etc., are just a few of the complicating problems which the circuit system designer must now consider. Each of the problems that are encountered in designing a simple circuit such as a multivibrator, an inverter, or a logical gate, must now be multiplied a hundredfold. Unless the designer has the ability to master the design of simple and basic circuit structures with lumped elements, he cannot hope to ever design a microcircuit or to put them together into a subsystem. We see, therefore, that even in this age of miniaturization and integrated electronics, knowledge of the design of simple lumped circuits is essential.

The microelectronics industry is today primarily involved in developing digital types of circuits for use in computers, military electronics, and space vehicles. The major area of consumer use of electronics—such as communications, television, radio, high fidelity equipment, heating, lighting and cooling controls, etc.—where reusability or repairability is essential and size and weight are not at a premium is still relatively untouched by microelectronics. However, this area is one of great and promising activity. In consumer applications, large power-handling capability, ease of maintenance, basic components designed to avoid obsolescence, and most importantly, cost, are factors which will insure that lumped element design will continue to be important to the electronics industry. Thus, microcircuit techniques and lumped element circuitry will probably be combined in all these areas for a long time. Again we see the need for engineers who can design circuits with lumped elements.

Another major reason for the need of such a text as this concerns engineering education. The student must be able to understand simple amplifying circuits utilizing a single transistor before he can appreciate the design complexities of a multistage amplifying circuit using five or six transistors contrived in a single chip of semiconducting material. He must appreciate the difficulties inherent in bias stabilization for the single transistor stage before he can comprehend the intricacies of stabilizing an entire microcircuit where the individual stages can interact and where the rise in temperature of one circuit indirectly affects all the others. He must clearly understand the workings of a single multivibrator before he can successfully design a miniature integrated-circuit shift register.

The study of electronic design incorporates not only circuit and network theory and electronic devices, but also ties together all of electrical engineering. Study in any part of this field requires an understanding of circuitry, whether in analog or digital computers, control systems, power generation and transmission, communications, instrumentation, or in all the rest of the vast domain of the electrical engineering technology. This unification is fundamental and must be made an important part of an electrical engineering education.

So much for the whys of the text. As to the hows, we have attempted to include under one cover a sufficient scope of topics, but with enough detail, to satisfy both the undergraduate and the graduate student, as well as the practicing engineer. We have assumed that the reader is familiar with the basic theory of operation of semiconducting devices, and therefore have included only one chapter on the theory. This first chapter is not rigorous, and serves mainly to refresh the memory of the reader, or to introduce simply the physical ideas which are important to an understanding of the operation of junction diodes and transistors. While not greatly detailed, this chapter serves to unify the topics covered in the bulk of the text by clearly laying the groundwork for the understanding of concepts such as temperature stability, frequency dependence, etc., which are important considerations in proper design.

Chapter 2 considers equivalent circuits for the transistor with emphasis on both the equivalent-circuit approach—the conventional matrix parameters such as h, y, or z parameters—as well as the physical parameters derived from the fundamental equations, such as the equation of continuity. Chapter 3 introduces the methods of biasing transistors, primarily to compensate for temperature variation in the operating parameters. However, the techniques of feedback, both shunt and series, as well as compound, are described and illustrated. Analytic techniques for evaluating and designing low-frequency untuned amplifiers are developed in Chapter 4.

Tuned amplifiers, which are still important in many consumer electronics are taken up in Chapter 5. The design of this type of circuit is crucial to the understanding of communications, tuned oscillators, detectors, etc., which are discussed in later chapters. The automatic gain control (AGC) feedback circuit so essential in many different types of equipment is discussed and analyzed.

Video or wide-band amplifiers, useful in television and FM receivers, are discussed in Chapter 6. These design techniques are exactly those necessary in the development of pulse amplifiers since their Fourier spectrum includes components with very large frequencies. Thus, this chapter serves to bridge the gap in the design of analog and digital circuitry. Chapter 7 discusses choppers and is a valuable addition to the text, as it clearly illustrates the advantages of semiconductor devices over mechanical devices (relays). The conversion of dc to ac necessary to enable the efficient amplification, modification, transmission, etc., of ac is readily accomplished by these circuits.

This leads directly to operational amplifiers discussed in Chapter 8. This is an all new chapter and is very design oriented. Again, this material is not generally available in electronics texts at this level, but is essential in the modern approach to design.

The operation and design of switching circuits are taken up in Chapter 9. These circuits include multivibrators, logical circuits (useful in digital computer development), and differing circuit schemes for connecting fundamental building blocks, such as binary counters (modified binary multivibrator) and gates, into ring counters, adders, and clock systems. The emphasis here is on the use of the bistable nature of the transistor in circuitry. However, since several simple circuits are put together to form a small system, this is the beginning of a look into the motivation for, and design, of integrated circuits.

In Chapter 10, we return to analog circuitry and discuss some aspects of the nonlinear behavior of the transistors. Here, the nonlinearity is utilized to effect control of a desirable oscillation, to mix two signals together, or to recover an information-carrying signal from an amplitude- or frequency-modulated carrier. This is still one of the most active areas for engineering designers and will continue to require engineers skilled in circuit analysis.

Discussion of the transistor operating in its nonlinear range is continued in Chapter 11 as the question of high-power amplifiers and frequency converters is taken up. Using the earlier discussion of tuned amplifiers as a background, we now go into the details of obtaining large power output in a narrow frequency range suitable for transmitters, etc. Noise behavior of transistors and their circuits is the subject of Chapter 12. The concept of noise figure and its measurement, fundamental in communications, is discussed and illustrated. In Chapter 13 we discuss two-terminal devices, similar to transistors, which can be used in certain applications. These devices can exhibit gain and are useful in both linear and nonlinear operation. They can be used as oscillators, amplifiers, switches, etc., and under certain circumstances are much to be preferred over their three-terminal counterparts. The use of the tunnel diode, backward diode, Gunn "diode," and avalanching pn junction diode are discussed. Because of their nature, these devices can be used at much higher frequencies than even the most modern transistors, and thereby extend the range of frequencies over which the circuit designer can function.

Integrated circuits are discussed in the two concluding chapters. This important topic is of an extremely specialized nature. No two circuits are identical, and since all devices within the subsystem or microcircuit are formed on the same chip, many new problems in design arise. These complications only add to the normal ones inherent in lumped element design, and require a volume of their own to be fully expounded. However, an attempt is made to introduce the circuit designer to the new demands and capabilities of the monolithic circuitry. By this means, we hope to convince him that certain considerations in lumped circuit design can be applied.and that others must be modified in order to design in this new domain.

A few exercises have been included at the end of each chapter to stimulate the interest of the reader and to provide some real design problems which can test his understanding of the material. No simple "plug-in" exercises have been used; the exercises are designed primarily to *amplify* the text material and to suggest real industrial designs.

The references at the end of each chapter are not meant to be exhaustive, but merely indicate other readily available text and journal material dealing with the subject. Since much of the subject matter in many of the individual chapters deals with material previously developed by other authors whose works contain adquate bibliographies, it was felt that no extensive referencing was necessary.

In summary then, considerable amounts of material have been added on modern transistor electronic devices and systems. However, we have maintained the direct approach to design, and continue to illustrate the use of these circuits with practical examples taken from widely used industrial applications. We have also eliminated some material which we felt was redundant, or no longer of wide interest, as well as reducing several of the mathematically tedious developments in the interest of improving readability.

We believe this is now a better and more modern book and we encourage your critical comments to improve it still further. Since my two co-authors for the earlier edition are now heavily committed to managerial functions in geographically widely separated regions of our nation, it has not been expedient to continue the collaboration for this major revision. However, the base of this text still amply represents the fruits of that earlier unity; and I am greatly indebted to both Charles Gray and John Ekiss for their willingness to allow me to continue to use much of their creative effort intact here. The original preface listed the many other contributors to that work and my continued indebtedness to these individuals is hereby acknowledged. It may also be of interest to the reader to note that my own career has changed direction somewhat, being less involved with solid state research and more with higher education and its management. I trust this does not detract from the text but perhaps even enhances its teachability.

Finally, I would like to thank all my students, colleagues, and former associates at Princeton University, Dartmouth College, and Drexel University who helped to guide my efforts and who provided useful critical reviews of the material by teaching or learning from it. My secretary of almost 2 years, Miss Connie Wallgren who typed and corrected the MS is to be especially commended for her untiring fortitude. I would especially like to thank Mr. James Chege of Prentice-Hall, Inc., for his invaluable assistance throughout the production of the book. To my wife who has put up with me for more than 20 years, I can only say gratefully, thank you.

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Overview of Appropriate Semiconductor Diode and Transistor Theory

INTRODUCTION

Since the invention of the transistor at the Bell Telephone Laboratories in 1948, it has found its way into varied applications in the commercial, industrial, and military fields. It is an active electrical device and because of input-output decoupling it can exhibit gain. Like the vacuum tube, the transistor finds its largest application as a control element, where a small input signal is used to control a large output signal as well as being useful as an on-off switch. Actually, in some applications, the gain is less important than the capacity for remote control of a given signal. In these so-called switching applications, the transistor has almost completely replaced the vacuum tube, gas tube, and relay because of its almost ideal characteristics.

This chapter does not present a rigorous treatment of semiconductor physics, because this is the subject of many books. Rather, we have attempted to present the information in a manner useful to circuit designers. Those interested in a more detailed discussion of semiconductor physics should consult the list of references.

PROPERTIES OF SEMICONDUCTOR MATERIALS

A *transistor* can loosely be said to be composed of two semiconductor diodes on a common piece of semiconductor material. These diodes are in very close proximity to each other, which affords a mutual coupling between the diodes. This is loosely referred to as *transistor action*. With this in mind, it seems only natural that the properties of semiconductor diodes should be the first subject of interest in studying transistors.

By way of review, a semiconductor is material that is neither a good conductor nor a good insulator, hence, the name *semiconductor*. An ideal diode is an electrically unilateral device; that is, current flows through it in only one direction. A practical diode approaches this ideal and under many applications can be said to approximate it quite closely. Why, one may ask, does the diode conduct in only one direction? In order to answer this question, we must first determine why any material does, or does not, conduct current.

BAND THEORY

In order for conduction to take place there must be, within a material, free electrical charges or carriers. A *free charge* is one that is not confined to any particular atom within the material. A material is classified as a conductor, semiconductor, or insulator depending on the number and mobility of these free carriers it contains per unit volume. The *mobility* of the carrier is, as its name implies, related to how mobile a carrier is in moving from one point to another.

In materials which have a regular, repetitive, atomic arrangement which we denote by the term *crystalline*, the outermost electrons from each atom find themselves bound to their nucleus more weakly than the inner electrons. Because of the Pauli exclusion principle, which can loosely be taken to imply that no two electrons can ever be in the same energy and momentum state, not all electrons can be at the lowest energy state possible. For a single atom, and for 0°K, energy levels can be schematized as shown in Fig. 1-1(a).* If we bring a second identical atom near the first we will now have an energy level scheme as shown in Fig. 1-1(b). The energy difference between pairs of levels is much larger than the energy difference within the pair itself. If we put many more identical atoms together, the energy structure becomes as shown in Fig. 1-1(c) where, because of the large numbers of discrete levels in each band, we have almost a continuous energy distribution within the band. Depending on the interatomic spacing of the crystal lattice structure, we will then have three rather distinct possibilities, as shown in Fig. 1-2.† These are shown in more detail in Fig. 1-3(a,b,c). Figure 1-3(a) shows a schematic band diagram of a metal where the interatomic spacing is large and the two outermost bands overlap so that electrons can freely go from one band to the other if we give them some thermal energy by raising the temperature. Because of this we will have many "free" electrons which can be moved in an external field thereby leading to a large current. Since the generalized Ohm's law between the cur-

*Here we plot energy as ordinate and momentum as abscissa (proportional to the inverse of interatomic spacing).

†Note that we now plot energy as a function of spacing and not momentum!