SEMICONDUCTOR ELECTRONICS

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PREFACE

MOST STUDENTS approach their first course in electronics with a sense of excitement and anticipation, and rightly so. They are aware of the impact electronics has on our society. They are also aware of the promises made by the electronics industry and the graduate schools that exciting careers are open for electronics engineers and scientists. As a result, they are generally a group of very highly motivated students.

The first course in electronics must present to these students some of the concepts and principles of electronics that will be broadly applicable in the remainder of their professional careers while at the same time maintaining their high level of interest and motivation. It is generally agreed that a basic understanding of the operating principles for electronic devices (excluding devices whose behavior cannot be properly understood without recourse to Maxwell's equations) and a basic competence in the analysis and design of circuits using these devices are two important components of the first course, regardless of the field of specialization a student ultimately selects.

It is also a fact that in today's crowded curriculum, the first electronics course may provide the only formal training many students receive in these two areas. The course must therefore provide a working knowledge of this material for students who will later specialize in information theory, control systems, and radio propagation, and even for those students whose major interest is in other branches of engineering or the basic sciences. At the same time, it must be a foundation course for students who elect to specialize in electronic device physics, device design, active network theory, or microelectronics.

My colleagues and I realized that even as late as 1960 our first course in electronics did not meet the needs of this broad range of students adequately, nor did it accurately reflect the needs and the state of modern electronics. The reasons for this seemed clear. The available texts for such a course gave about equal coverage to vacuum tube and semiconductor electronics, whereas the vast majority of electronic circuits and systems that modern engineers and scientists come into contact with, whether as users or designers, employ solid-state components. The available texts also gave considerably more emphasis to the formal analysis of electronic circuits than to flexible principles of circuit design; and they gave only a survey coverage to the physical principles that determine the behavior of electronic devices, particularly semiconductor devices. By contrast, many of the exciting careers in electronics that industry and the graduate schools advertise are for students who have a thorough grasp of the physical principles that govern solid-state device behavior and who have the ability to design electronic circuits using new solid-state components.

It seemed clear to us that it was time for a fresh start. Accordingly, I was given the opportunity of beginning a series of pedagogical experiments aimed at producing an entirely new first course in electronics—not an updated revision of an existing course. The first experiment consisted of a two-quarter sequence of lectures (about 60 one-hour lectures in all), given to a volunteer group of about 20 junior-level students in electrical engineering plus a few physics, chemistry, and physiology majors with a prior interest in electronics. The aim of these lectures was to give the students (1) a firm physical grasp of what holes and electrons are and how they behave in semiconductors; (2) a clear understanding of the effects that occur at a *pn* junction when bias is applied to it; (3) valid physical descriptions (quantitative and qualitative) of how junction diodes and transistors operate; (4) an understanding of the processes by which models are made, for both circuits and devices (and in particular the need for making key approximations); and (5) realistic experience in designing amplifiers, oscillators, and simple switching circuits.

I attempted to keep the center of attention focussed on major effects, all of which are relatively simple. The lectures did not delve deeply into subtle physical phenomena or extreme sophistication in circuit design. At the same time, they were definitely not intended to be a survey in any way. I also wanted to make sure that adequate attention was given to experimental electronics, and that the equal partnership of theory and experiment was emphasized. To accomplish this objective, a number of lecture demonstration experiments were developed to give the students an appreciation of basic experimental realities and some insight into the quality of the agreement between theory and experiment. I also had the students build some simple circuits (a power supply, an audio amplifier, an oscillator, and a multivibrator) as part of their homework. The circuits had to meet certain specifications, and were graded with meters and oscilloscopes whose scales were marked off "A, B, C, D" according to how nearly the circuit met the prescribed specifications.

The course met with an enthusiastic reaction among the volunteer group of students. It therefore seemed reasonable to try it next on a larger group of students. To accomplish this, a limited preliminary edition consisting of some of the lecture notes (particularly those topics that were unavailable in other texts) together with instructions for building some of the demonstrators was published. This preliminary edition was used by electronics teachers at a number of schools across the country and by teachers in the Electrical Engineering Department at Stanford who had little prior experience in teaching semiconductor electronics. It was also used by me and by other teachers as the basis for industrial "in-house" courses for practicing electrical engineers who grew up in the vacuum-tube era, and for self-study by a number of individual students at Stanford (primarily mathematics and physics majors for whom electronics was a hobby). Finally, the preliminary edition was carefully reviewed by teachers who did not use it in class but who were thoroughly familiar with the subject matter.

This extensive testing produced many valuable suggestions that have been incorporated into this book. In particular:

1. A number of new experiments have been included and old ones have been revised to be more effective. Experimental techniques and results are described in detail at appropriate points in the text, using oscilloscope traces and other direct records of experimental performance. This approach gives the student an appreciation of experimental problems and it permits him to make calculations by using experimental data and thus to compare theory and experiment without actually seeing the experiments performed.

2. A large number of numerical examples have been introduced, particularly in the sections on circuit design.

3. All circuit-design examples use data taken directly from transistor data sheets rather than "typical" parameters.

4. The basic ideas necessary to understand the operating principles and applications of vacuum tubes have been included, using the same theory-and-experiment format found elsewhere.

To insure that the basic aims and philosophy were not diluted by the increase in book length that was necessary to incorporate these suggestions, certain key chapters of the final book were made available to a cross-section of students, teachers, and reviewers for their comments. Their reactions suggest that the book will satisfy serious students in electronics, whether they intend to specialize further in this subject or not.

Preparation. For the most part, I have attempted to write the book for students of a certain level of scientific maturity rather than a specific background preparation. The maturity level assumed at the outset is that of a beginning junior in electrical engineering or physics. By this I mean that the students have either had or can quickly learn (from listed references) the elements of Fourier analysis, some basic atomic physics, and some basic circuit theory.

As the subject unfolds, a mastery of mesh and nodal circuit analysis, in both its differential equation and Laplace transform aspects, is required. Electrical engineering majors who take the course at Stanford obtain this material from a concurrent course in network analysis; again references for additional reading are provided at appropriate points for students who are not taking the circuits course. The references have proved to be an acceptable substitute, though a progressive increase in maturity level of the student is required.

Teacher's Manual. The book has been organized so that fundamental ideas are presented at the beginning of each section and elaboration follows. The intention here is to provide for flexible use of the book by those who have specific needs and specific limitations. The entire book can readily be covered in a full academic year (90 lectures). Suggestions for courses of 15, 30, 45, and 60 lectures are given in the Teacher's Manual for *Semiconductor Electronics,* together with solutions to selected problems.

Acknowledgments. It will be evident from earlier statements that I am heavily indebted to many people for their contributions to this book. I particularly want to acknowledge the positive influence of many stimulating discussions I have had with students who have taken the course, both at Stanford and in industry. Their reactions, together with comments and reactions from teachers and students at other universities, have helped to provide the encouragement necessary for carrying out the work.

I am also indebted to my colleagues in the Electrical Engineering Department at Stanford, not only for giving me the opportunity to develop this course, but also for much assistance and encouragement along the way; and to the University administration in general and Professor J. G. Linvill in particular for creating an environment in which I have been encouraged to do research work, graduate teaching, and industrial consulting in semiconductor electronics. Writing an undergraduate text on the subject would have been difficult indeed without this background.

Finally, I am indebted to Professors J. G. Linvill, D. F. Tuttle, and R. J. Smith, and several members of the Semiconductor Electronics Education Committee for many useful discussions that have helped shape the philosophy of the book; to Professor G. L. Pearson and Mr. K. G. Sorenson for assistance in preparing demonstration experiments; to Mrs. M. Cloutier for expert secretarial services; and to the McGraw-Hill Book Company for making the book available in a preliminary edition.

J.F.G.

CONTENTS

INTRODUCTION

ELECTRONICS is the rather vague name that is usually applied to a broad field of activities, all of which are in some way concerned with the generation, transmission, and reception of *information*. To begin our studies of this subject, it will be helpful to introduce some basic ideas and briefly describe some typical electronic systems so that we can obtain a somewhat clearer picture of just what electronics is, and how the topics which receive the greatest attention in this book are related to the whole.

The word "information" has been italicized in the definition of electronics because this is a primary characteristic which distinguishes an "electronics" system and electronics engineering from a "power" system and power engineering. Some examples will elucidate this distinction.

Any electric current has two attributes of fundamental importance: it carries *energy* and, in a suitably defined sense, it carries *information*. The sense in which information is carried is that the form and/or presence of an electric current implies that an event has happened.[1]

These two attributes of an electric current are inseparable, though frequently one of them is of primary interest. For example, the fact that a light bulb is on conveys the information that a certain sequence of switches is closed, that the electric power station is operating, and so on. However, the power generation and distribution system is constructed to energize the light bulb, not to answer questions about the positions of various switches. On the other hand, a radio transmission and reception system is designed for the primary purpose of conveying information. The form of the electric current which drives the loudspeaker enables us to identify the sounds that originate in the broadcast studio. We may wish to ensure that the speaker creates sufficient air-pressure variations to make the sound clearly audible, so we shall be concerned with the energy content of the electric current supplied to the speaker. However, the energy content is not the most important attribute of the electric current in this case. We classify a system as being electronic if the *information content* of the currents and voltages in it are of most importance. A power system is one in which the *energy attribute* of the current is the key factor.[2]

We usually refer to a quantity that carries information (a current, a voltage, or a sound-pressure variation, for example) as a *signal*. In an electronic system, we are concerned with transmitting signals from their point of origin to a desired destination, and then presenting them in an appropriate way to an observer. The signal may change its form several times during this process, though finally it will be reconstructed in a way which enables the observer to understand the message.

It is convenient to represent the signal processing that occurs in an electronic system by means of a block diagram; that is, a set of interconnected boxes in which each box performs an assigned signal-processing function. The boxes are simply labelled in the diagram according to the function they perform. We shall use this technique to illustrate some of the types of signal processing that occur in electronic systems common to our everyday experiences. The names of certain of the boxes, which are also called functional blocks or subsystems, will be italicized when they are first mentioned. The components needed to build these (and many other) subsystems, the manner in which the components are connected to achieve the desired subsystem functions, and the overall performance characteristics

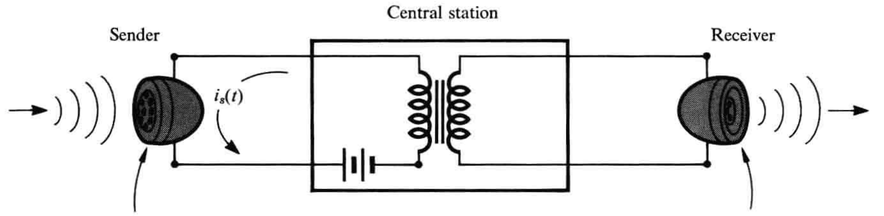
[1] We shall expand on this definition specifically in Chap. 16 and by examples elsewhere in the text.

[2] Electrical engineering is not cleanly divided by this definition (for example, a power supply in a radio receiver is part of an electronic system in which the energy content is of greatest importance), but it is more adequate for our purposes than other definitions based on light or heavy currents, power flow, the importance of electronic phenomena, and so on.

of the resulting systems and subsystems will be discussed at length in various parts of the book.

Signal processing in some electronic communication systems. As our first example, let us consider the simple telephone system shown in Fig. I · 1*a*. We shall take the original signal in this system to be the air-pressure variations created by the person speaking. These air-pressure variations are directed at the carbon microphone in the telephone handset, where they produce corresponding fluctuations in the resistance of the microphone. In the simplest system, a dc voltage is applied to the microphone through wires that connect the telephone set to a "central station." The amplitude of the current that circulates in these wires is inversely proportional to the instantaneous resistance of the microphone, and is thus a measure of the instantaneous air pressure at the microphone. The variations in amplitude of this current with time contain the spoken message.

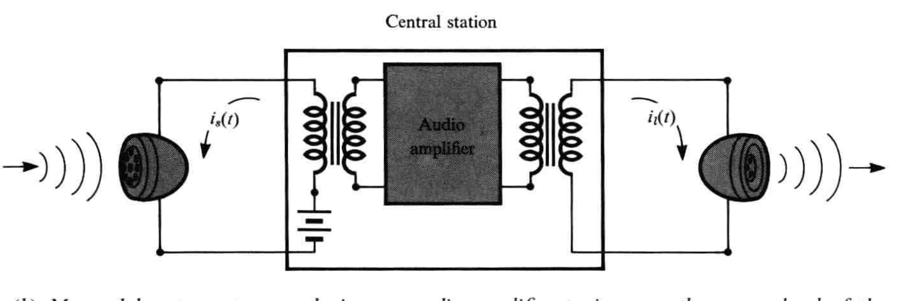
The spoken message can be reproduced by causing a replica of the signal current $i_s(t)$ to flow in an earphone at the receiving end. In the earphone the current flows in a coil of wire with a diaphragm attached to one end of the coil. The coil is placed in a local magnetic field produced by a



Carbon microphone in which the resistance varies with the instantaneous air pressure on the diaphragm, producing a current whose time-variable part $i_s(t)$ contains the message to be transmitted

Handset earphone in which sound-pressure variations are produced by a flow of the current $i_s(t)$ in a field-coil winding

(a) Partial illustration of a simple telephone system, mod I



(b) More elaborate system employing an audio amplifier to increase the power level of the signal before sending it on to the receiver

FIG. I · 1 SOME COMMON ELECTRONIC SYSTEMS FOR COMMUNICATION

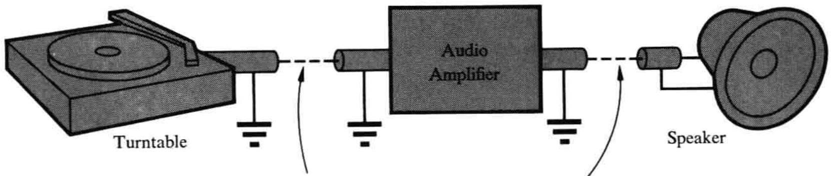


FIG. I · 2 BLOCK DIAGRAM OF AN AUDIO REPRODUCTION SYSTEM

small bar magnet, so that current flow in the coil produces motion of the diaphragm. The earphone thus reconverts the electrical signal into a sound-pressure signal.

The energy content of the signal current $i_s(t)$ is large enough so that with fresh batteries and a properly selected transformer to couple the earphone and microphone, telephone communication over several tens of miles can be established with the simple system shown in Fig. I · 1*a*. However, for greater distances, it is necessary to increase the energy content of the signal before sending it on to the receiver. This can be accomplished in an *audio amplifier,* which is located in the central station (see Fig. I · 1*b*). By using a pair of amplifiers (or other possible techniques), a two-way communication can, of course, be established between the two parties.

A basically similar system to that shown in Fig. I · 1 is the general audio reproduction system shown in Fig. I · 2. This system consists of a loudspeaker, an audio amplifier, and a "program source." If our program source is a record, the original signal is the information contained in the grooves that are made in the record during the recording (or record-reproduction) process. The phonograph cartridge converts this information into a voltage whose amplitude is proportional to the instantaneous sound pressure which we wish the speaker to reproduce. However, the available output power from the phonograph cartridge may be only 10^{-10} watt, whereas we may want to deliver 1 watt of signal power to the voice coil of the loudspeaker to develop a suitable volume of sound. Again, the audio amplifier supplies the required increase in signal power.

We can modify the foregoing concept or change certain details to build public-address systems, "stereo" sound systems, and so on. However, all these systems are built with the assumption that the distance between the sender, or original signal, and the receiver is small; or that wires can conveniently be used to connect the sender and receiver. When communication over long distances is required, such as in radio broadcasting or long-distance telephony, then changes in the system operating philosophy must be made to make it economically feasible.

In a radio broadcast, for instance, we may want a transmitter to provide signals at all points within a radius of a few hundred miles. To do this, we radiate or broadcast electrical signals out into space by forcing a signal