MICROELECTRONIC DEVICES AND CIRCUITS

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Dedicated to the memory of my father, Clifton G. Fonstad, Sr.

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ABOUT THE AUTHOR

Clifton G. Fonstad is a full professor in the Department of Electrical Engineering and Computer Science at the Massachusetts Institute of Technology (MIT). He received his BS degree in 1965 from the University of Wisconsin, Madison, and his MS and Ph.D. degrees in 1966 and 1970, respectively, from MIT. He conducts a large and active graduate student research program concerned with the application of InGaAlAs heterostructures grown by molecular beam epitaxy in a variety of advanced electronic and optoelectronic devices. With his students he has authored or coauthored over 100 technical publications on such topics as heterojunction bipolar transistors, resonant tunneling diodes and three-terminal quantum-well-base tunnel-barrier devices, quantum well intersubband transitions, and semiconductor laser diodes. Professor Fonstad has taught the basic physics, modeling, and application of semiconductor devices for over 20 years at MIT, and for many years was responsible for the microelectronics teaching laboratory. He is currently in charge of Electronic Devices and Circuits, the header course of the Devices, Circuits, and Systems concentration in the Department's new 5-year Masters of Engineering curriculum. He is faculty supervisor of the MIT Center for Materials Science and Engineering Microelectronics Technologies Central Facility and serves as chairman of the MIT Microsystems Technology Laboratory Policy Board. He is also the project leader of a directed project on Very Large Scale Optoelectronic Integrated Circuits in the National Center for Integrated Photonics Technology. He is a member of the Institute of Electrical and Electronics Engineers and of the American Physical Society. Professor Fonstad enjoys woodworking and such outdoor activities as running, hiking, camping, and canoeing; he regularly commutes to and from MIT by bicycle.

PREFACE

Most books exist because the authors felt that there were no other books that said what they felt needed to be said in the way they wanted to say it. I felt that a different book was needed, too, and this book is my attempt to fill that need. This text is "different" for what it does not include as well as for what it does include, and this uniqueness merits some discussion.

First, this text *does* span a range of topics from semiconductor physics to device function and modeling to circuit analysis and design. It is a basic premise of this text that it is important in a first course on semiconductor electronics to address this broad range of topics. Only in this way can we adequately emphasize from the beginning the interactions between physics, devices, and circuits in modern integrated system design.

Second, this text *does not* include, except as an appendix, semiconductor band theory or any of the associated theoretical baggage that implies (e.g., Fermi statistics, effective mass theory, etc.). It is another basic premise of this text that such material is best left for later, specialized courses and is in fact not necessary for a first, thorough treatment; you do not need to understand energy bands to understand *p-n* junctions, bipolar transistors, and FETs. As a consequence this text can be used by college sophomores who have had only a basic introduction to physics and circuits. More importantly, by teaching no more semiconductor physics than is necessary to understand the devices, this text can place more emphasis on actually developing this understanding.

Third, this text *does* take as its mission to teach the broader topic of modeling using semiconductor electronics as a vehicle. Therefore it is a text that should be of value to all engineering students. If you learn something about semiconductor electronics, so much the better, but you will certainly gain an appreciation of the issues inherent in developing and applying physical models.

At the same time, this text *does not* emphasize the use of sophisticated computer models. The focus here is instead on understanding and choosing between various approximate models to select one that might be suitable, for example, for a back-of-the-envelope calculation, estimation, and/or evaluation of a design concept. Computer models have their place and are extremely important for engineers, but in a text at this level they are more dangerous than anything else since they tend to work against developing the insight we seek.

Fifth, this text *does* include design, as well as analysis. Design is admittedly not a main focus, nor is much time devoted specifically to it, but some design excercises are included, and a design experience is recommended as a complement to any course based on this text. Only through the exercise of design—of, for example, choosing a circuit topology and, given a topology, selecting component values to achieve certain performance goals—can the lessons of this text be truly learned.

Sixth, this text *does not* attempt to be the final word on any of the topics it addresses. It presents a correct first treatment and imparts a functional level of knowledge, but it is also only preparation for a second tier of specialization, be it in physics, devices, circuits, and/or systems, that surely must follow.

Seventh, this text *does* contain much more material than can be covered in any one course; yet, eighth, an instructor using this text *does not* have to use all of this material, nor, in fact, does he or she have to use it in the order it appears in the table of contents. I have attempted to write this text in such a way that it is possible to use many different subsets and orderings of the material, and in such a way that discussions of more advanced modeling and of more specialized and less pervasive devices can be skipped over without loss of continuity. (Please see "Comments on Using This Text" below for more on these points.)

Also, this text *does* have its roots in a long legacy of semiconductor electronics education at MIT, and none of the preceding litany of do's and don'ts are claimed to be original to this text. In 1960 the Semiconductor Electronics Education Committee (SEEC) was formed under the leadership of MIT faculty members to address the question of undergraduate electrical engineering education in light of the dramatic changes that were then taking place in the field of electronics with the advent of the silicon transistor and integrated-circuit technology. An important product of that effort was an appreciation for the close coupling between semiconductor physics, device modeling, and circuit analysis and for the value of teaching these topics in a coherent unit. The SEEC produced an excellent, very carefully written series of seven paperback volumes and led indirectly to the publication of a textbook: *Electronic Principles—Physics, Models, and Circuits* by Paul E. Gray and Campbell L. Searle (Wiley, New York, 1969). The present text unashamedly builds upon these SEEC foundations. It addresses a similarly broad range of topics at a similarly accessible level, differing primarily only in that it does so in a way that reflects the field of semiconductor electronics as it exists now over 30 years after SEEC (i.e., in the 1990s).

COMMENTS ON USING THIS TEXT

As stated earlier, I have attempted to write this text in such a way that it is possible to use many different subsets and orderings of the material, and I have used it to teach the subject 6.012—Electronic Devices and Circuits at MIT following several topic sequences. The order in which the material appears in this text is a relatively traditional one and it works well. It does, however, mean that circuits are discussed only after a considerable amount of time has been spent on physics and devices. A convenient, timely way to get circuits in sooner is to present the MOSFET before the BJT, and to discuss MOS logic circuits right after finishing the MOSFET. When doing this, I have found that it is useful to follow the text through the reverse biased *p-n* diode (Section 7.2) so the depletion approximation has been introduced, and to then go to Chapters 9, 10, and 15 before returning to Chapter 7 and continuing with Section 7.3.

Chapters 14 and 16 contain material that can also be presented earlier with good effect. One can easily argue that all of the material in these chapters could have been integrated into the earlier device and circuits chapters, but I resisted doing this because I feel it is useful to have the discussions of frequency response collected in one place; the same is true of the switching transients discussions. Having said this, however, I do usually include the discussion of switching times of MOSFET inverters with the discussion of their other characteristics. Another example is the switching transient of a *p-n* diode, which is a good issue to discuss soon after teaching diode current flow. The fact that there are plenty of carriers to sustain a reverse current immediately after a diode has been switched from forward to reverse bias is easy to see, and it reinforces the students' understanding of current flow in a diode.

Finally, it is important to realize that we are unable to cover all of the material in this text in our one-semester course at MIT. Typically, we wait until a senior-level device elective to cover the more advanced device models; to discuss JFETs and MESFETs, optoelectronic devices, memory, and bipolar logic; and to cover much of the discussion of large signal switching transients. I recommend considering the following topics and sections (section numbers in parentheses) when you are looking for material to delete or de-emphasize: physics issues such as high-level injection solutions (3.2.3) and certain boundary conditions (5.2.3 c–e); advanced models for diodes (7.4.1b), BJTs (8.2.1b), and MOSFETs (10.1.1b); and certain more specialized or less pervasive devices such as photoconductors (3.3), photodiodes (7.5), LEDs (7.6), phototransistors (8.3), JFETs (10.2), MESFETs (10.3), memory cells (15.4), and charge-coupled devices (16.2.2b). If, on the other hand, you are looking to expand upon, or add to, any of the material in the main text, there is ample material in the appendices presented at much the same level on energy bands, Fermi statistics, and the effective mass picture (Appendix C), on metal-semiconductor junctions (Appendix E), and on processing (Appendix G).

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First and foremost, I thank my wife, Carmenza, and my sons, Nils and Diego, for their support, tolerance, and love throughout this project.

The present text reflects very much the philosophy of the late Professor Richard B. Adler, who had a great influence on me since the day I first set foot on the MIT campus. Many others, including Professors A. C. Smith, R. F. Morgenthaler, D. J. Epstein, and R. H. Kyhl, have also taught me a great deal about this material and how to teach it over the years, and I gratefully acknowledge their influence and impact on me and this text.

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Finally, I welcome further comments, suggestions, or corrections from users of this text; I invite you to communicate with me by electronic mail (fonstad@mtl.mit.edu).

Clifton G. Fonstad

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Appendixes

CHAPTER 1

MODELING

The title of this text is *Microelectronic Devices and Circuits*, but it is really a book about modeling. Inevitably, this focus will tend to be neglected as we concentrate on learning how semiconductor diodes and transistors work and how they are used in analog and digital circuits. Thus, it is important that we start with a few comments on models and on our hidden agenda.

1.1 GENERAL COMMENTS

You are familiar with models for circuit components—resistors, capacitors, inductors, wires—and you have learned that, for example, the terminal current-voltage relationship of a real resistor that you might get from a stockroom or buy at an electronics store may be represented, or modeled, by an "ideal" resistor for which $v_{RR'} = i_R R$, where $v_{RR'}$ is the voltage difference between the two terminals of the resistor, i_R is the current into the positive reference terminal (and out the negative terminal), and R is the resistance of the resistor, in units of ohms (Ω). We tend to think of this model when we encounter an actual resistor, and the distinction between a real resistor and the model becomes blurred. This is all right as long as we do not lose sight of the fact that $v = iR$ is just a model, and that as such it has limitations. For example, if we change the temperature of a resistor, its R value will change, and at very high current levels, the variation of voltage with current is no longer linear, in part because of internal heating. An important part of learning a model is learning its limitations, and an important part of using a model is remembering that it has limitations and knowing what they are.

In this text, one of our objectives is to develop accurate models with as few limitations as possible. We also want models that are useful. By "useful" we mean models that are analytical and, often, that are easy to use in hand calculations. We also mean models that are conceptual and through which we can gain insight into problems. Not surprisingly, the two objectives of utility and accuracy are not always consistent, and compromises usually must be made. This often leads to a hierarchy of models for a device, ranging from the very simple and approximate to the very precise and complex. An important part of modeling and analysis is knowing which model to use when.

The real value of a good model is that it lets us predict performance. It lets us improve, modify, and apply; it lets us design new things, not just analyze old ones; and it provides a high degree of confidence that what we design will work. The most successful models are founded on an understanding of the physical processes at work in what is being modeled. Such models are conducive to the development of physical insight, and they are essential for predicting the unknown.

To illustrate the importance of understanding the physics of a process in order to develop useful models for it, we can look at two examples where the physics is not yet understood, and thus for which models capable of predicting performance do not exist: high-temperature superconductivity and cold fusion. In the first instance, people ask, "Can we make a room-temperature superconductor? If not room temperature, how high?" We cannot even pretend to answer these questions without understanding the basic mechanism behind the lack of resistance in the new "high-temperature" superconductors. The same is true for cold fusion. We cannot predict whether test-tube fusion will be a useful source of energy, nor can we begin to improve upon the minuscule amounts of energy produced thus far without understanding the physics of the phenomenon, that is, without a model for it.

As a final example, let us look at models for our planet and at how those models evolved. Hundreds of years ago, many fairly isolated civilizations existed, all of which had developed models for the universe. In the Western European civilization there were two competing models: the flat-earth model and the round-earth model. There was also a great deal of interest among businessmen in developing trade with the Chinese, Indian, and other Far Eastern civilizations; and depending on which model of the earth you believed in, you saw different possibilities for getting to the Far East. According to both models, you could go directly east over land, but that was known to be both dangerous and difficult. Both models also indicated that you might be able to sail along the coast of Africa, but this journey was also very dangerous. The round-earth model suggested a third route, namely, west. According to the model subscribed to by Columbus, sailing due west would be a long, but practical, way of getting to the Far East.

On the one hand, the model Columbus used, which was based on a better physical understanding of the solar system, was the more correct; it gave him the confidence to sail west from Spain without fear of sailing off the edge of the earth into an abyss. On the other hand, the model had some serious flaws and needed to be modified. For one thing, the model didn't include North and South America, but that was not a fatal flaw. More important for Columbus, his model didn't use the right diameter for the earth, so he thought the Far East would be a lot closer than it was. At that time many scientists thought the earth was bigger than Columbus did; and, ironically, if Columbus had believed the big-earth advocates (who were right, after all), he might not have even tried to sail west, since he could not have carried all of the provisions needed on the ships then available. The colonization of America might have been delayed a few years, but bigger boats and a belief in the round-earth model would eventually have led someone to sail west.

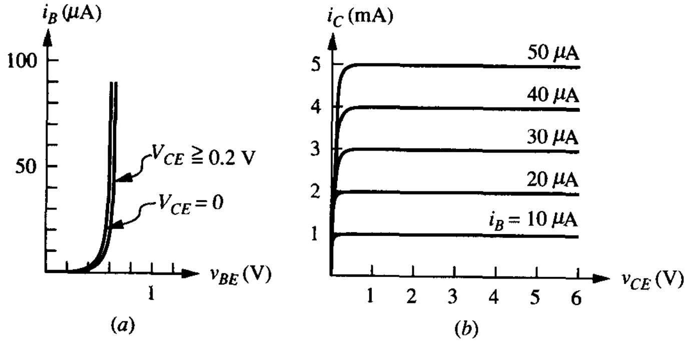
Today we know that the earth is round and we know how big it is, but how often do we use the round-earth model in daily life? For most of what we do, a flat-earth model is perfectly adequate and much easier to work with. Mathematically, we recognize that the flat-earth model is a linear approximation to the round-earth model, valid for motion in our immediate vicinity. In circuit jargon, we would call it a small-signal, or incremental, linear equivalent model for the earth.

There are many different models for the earth, ranging from a flat slab to an infinitesimal point, and each has utility in the right situation. One of the important things to learn about modeling is how to trade off complexity and accuracy, and how to choose the appropriate model for the task at hand.

1.2 EMPIRICAL DEVICE MODELS

Consider the bipolar transistor. You are familiar with its terminal characteristics, shown in Fig 1.1, and with the large-signal and incremental models for the bipolar transistor, shown in Fig 1.2. You might legitimately ask, "Don't I know enough? Why do I need to bother with a lot of physics and spend an entire semester learning more about transistor models?"

The problem is that so far these models are only empirical. We got the large-signal model by measuring a device's characteristics and then mathematically fitting those measured characteristics to an ad hoc collection of ideal circuit components—model building blocks, if you will—that give the same behavior of terminal currents and voltages. In general, more than one combination of components will give the same terminal characteristics, but experience with several devices and a little common sense helps us select a model topology that doesn't



(*a*) (*b*)

FIGURE 1.1
Input (*a*) and output (*b*) families of terminal characteristics for an *npn* bipolar junction transistor (BJT).

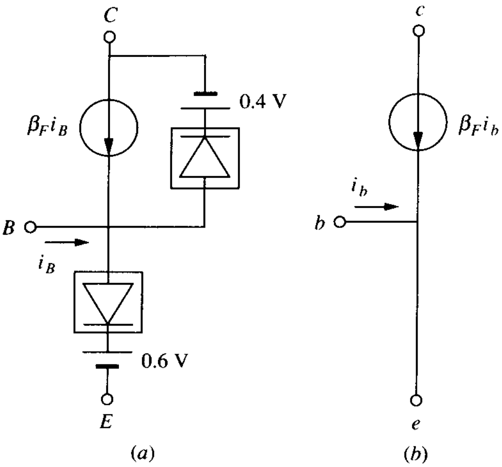


FIGURE 1.2
Large-signal (*a*) and incremental (*b*) circuit models for the terminal characteristics of an *npn* bipolar junction transistor.

change dramatically from device to device, a topology that somehow "fits" the bipolar transistor. We may develop confidence that our model is "right" for the bipolar transistor, but it is purely empirical, with only a fortuitous connection at best to the internal workings of the device. Based on this model, we have no way of knowing if, for example, there is any way of changing the diode breakpoint values of 0.6 V and 0.4 V. We don't know what determines β and how it can be changed, what happens if the temperature is raised or lowered, or whether the device will work at 1 GHz or with 100 A of collector current. We don't even know whether we have to ask such questions or if there are other, more important questions we should be asking. With empirical modeling, what you've seen is what you've got, and if you want to try something new, you have to take some new measurements.

We want to go beyond empirical modeling to develop models based on the physics of devices so that we can answer such questions with some generality and confidence, before doing extensive measurements. More important, we want models that will let us predict the unknown.

1.3 WHY SEMICONDUCTORS? WHY TRANSISTORS?

The need to learn modeling should now be clear to you, but the choice of semiconductor transistors as the context in which to study modeling may not be. Today electronic system design has very much become integrated circuit design. Thus, whereas at one time an engineer could specialize either in devices or in circuits or in systems, it is now impossible to separate systems from the semiconductors