COMPLETE GUIDE TO SEMICONDUCTOR DEVICES

Kwok K. Ng

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ABOUT THE AUTHOR

Kwok K. Ng received his Ph.D. degree from Columbia University in 1979 and B.S. degree from Rutgers University in 1975, both in Electrical Engineering. He has been with AT&T Bell Laboratories at the Murray Hill location since 1980, engaging in different aspects of silicon VLSI devices and technologies. Dr. Ng has been active in contributing to journal papers, conference talks, book chapters, and holds various patents. He is a Publication Committee member of the IEEE Electron Devices Society, and a former Associate Editor of *IEEE Electron Device Letters*.

ABOUT THE BOOK

Complete Guide to Semiconductor Devices provides an overview of a *complete* collection of semiconductor devices. As a *guide*, the essential informations are presented for a quick, practical, and balanced survey.

Each short chapter is devoted to only one specific device and is self-contained, enabling the readers to go directly to the intended device. Chapters are written to be independent with minimum cross references to other chapters.

A special format for each chapter answers basic questions about each device: (1) History–when was it invented and by whom? (2) Structure–how is it made? (3) Characteristics–how does it work? (4) Applications–what is it for?

With a final section–Related Devices–added to many of the 67 chapters, more than 180 device structures are covered, and more than 800 references cited for further in-depth studies. Together with more than 480 illustrations and extensive appendixes, *Complete Guide to Semiconductor Devices* is a pragmatic handbook that offers an engineering approach to the study of semiconductor devices.

INTRODUCTION

It is difficult to have a clear quantitative definition of semiconductor. Based on conductivity, materials can be classified into three groups: (1) metal (conductor), (2) semiconductor, and (3) insulator (non-conductor). A general guideline indicating their ranges of conductivity is shown in Fig. I.1. Note that one important feature of a semiconductor is that it can be doped with impurities to different concentration levels, so every semiconductor material can cover a range of conductivity. The total range of conductivity for semiconductors is from 10^{-8} S/cm to 10^3 S/cm (resistivity from 10^{-3} Ω-cm to 10^8 Ω-cm).

The conductivity of materials is ultimately related to the energy-band structure as shown in Fig. I.2. For an insulator, the energy gap E_g is large. Consequently, the valence band is completely filled with electrons, and the conduction band is completely empty. Since current is a movement of electrons, and electrons need available states to move to, current cannot be generated from a completely filled band and a completely empty band. A semiconductor has a smaller E_g. Even when the Fermi level is within the energy gap, thermal energy excites electrons into the conduction band, and some empty states are left behind in the valence band. These partially filled bands make electron movement possible. In a metal, the energy gap is even smaller, and the Fermi level resides within either the conduction band or the valence band. Another possibility for a metal is that the E_V is above the E_C so that the two bands overlap, and there is no energy gap. In such a system, the Fermi level can be in any position. Since for the semiconductor, the Fermi-Dirac statistics are necessary to determine the electron populations, temperature is also a crucial factor. At a temperature of absolute-zero, all semiconductors would become insulators. For practical consideration, at room temperature, semiconductors have energy gaps ranging from ≈ 0.1 eV to ≈ 4 eV.

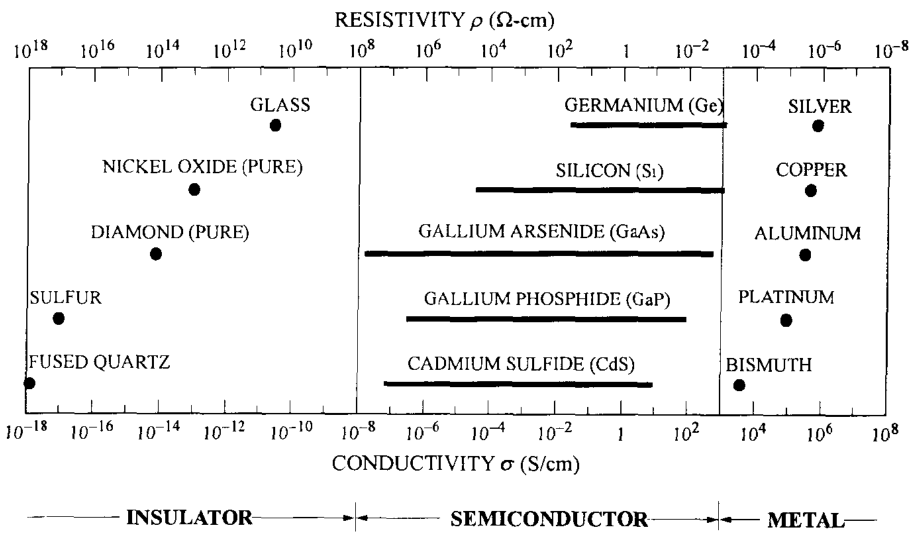

FIGURE I.1
A semiconductor is distinguished from the insulator and the metal by the range of resistivity (or conductivity) it spans. Note that, unlike the metal and insulator, each semiconductor can be doped to vary its resistivity. (After Ref. 1)

For a historic perspective, some common electronic devices with the years they were developed are shown in Fig. I.3. The earliest device, not necessarily made of semiconductor material, is probably the resistor, implied by Ohm's law back in 1826. Vacuum tubes started around 1904, and were the major electronic components in the early radio era through World War II. The real birth of the semiconductor industry was in 1947 with the invention of the bipolar transistor. Ever since, new semiconductor devices have been invented at quite a steady pace, although some are more commercially significant than others. Figure I.3 shows only the more common kinds. There are some devices whose development is too gradual to assign a milestone. An example is the solar cell. Starting from the mid-1970s, with the advent of MBE and MOCVD technologies, there are numerous heterojunction devices that are also omitted because it is too early for them to have an impact commercially.

Currently, there are more than 100 semiconductor devices. To include such a large collection, the hierarchy of semiconductor devices used in this guide needs to be clarified. This also explains why certain devices are put in separate chapters. Figure I.4 shows that, for example, the LED, laser, solar cell, and tunnel diode are all variations of a *p-n* junction. But since each of these is made for a special purpose, their designs consider different device physics, and their structures are very different. A person who wants information about a solar cell, which receives light and converts it into electrical power, does not have to understand how a *p-n* junction emits light in an LED. It is for these reasons that a total of 67 major devices are identified and put into individual chapters. For the next level of variation, the deviations are relatively minor and additional materials needed to describe them do not require separate chapters. These devices are attached to some of the major devices as "related devices." The total number of devices falling into this category is found to be 114. This, of course, will change with time and rearrangement might be necessary for future editions. It is intentional that this guide includes older devices that have become obsolete. Old information is important to avoid duplication of effort, and is often the ground for new concepts.

The word *complete* in the book title refers to the inclusion of all devices, to the best of the author's knowledge. It does not mean complete in covering details on every device. References are always given if the readers are interested in more in-depth studies. As a *guide*, this book presents only the key background, principles, and applications.

To help gain a better perspective on this large variety of devices, chapters are ordered according to their functions or structures, with group names assigned to describe them. This also provides a means for comparison among devices in the same group. These groups are:

1. Diodes: I–rectifiers
2. Diodes: II–negative resistance
3. Resistive devices
4. Capacitive devices
5. Two-terminal switches
6. Transistors: I–field-effect
7. Transistors: II–potential-effect
8. Transistors: III–hot-electron
9. Nonvolatile memories
10. Thyristors
11. Light sources
12. Photodetectors
13. Bistable optical devices
14. Other photonic devices
15. Sensors

While most of these group names are self-explanatory, a few need clarification. The name diode comes from vacuum tubes, and refers to a 2-element diode tube. Other vacuum tubes are the triode tube, tetrode tube, and pentode tube, with the number of active elements being 3, 4, and 5, respectively (see Appendix A1). Since in the diode tube, the cathode emits only one kind of carriers–electrons–the diode tube has asymmetric *I-V* behavior and is a rectifier. Although semiconductor diodes inherited the name, some of them actually do not have

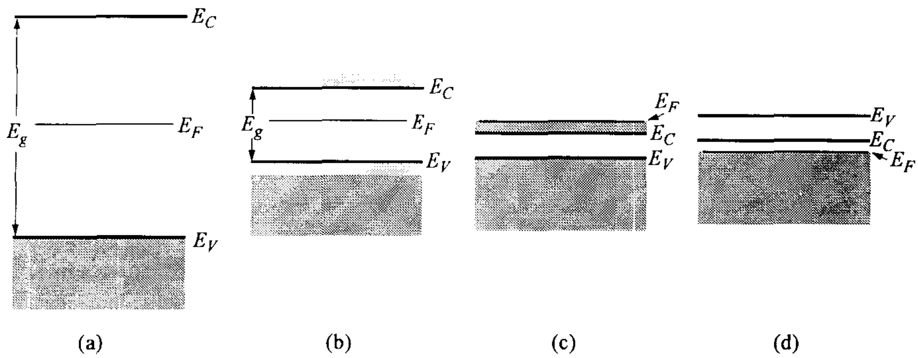

FIGURE I.2
Energy-band diagrams showing that (a) in an insulator, the bands are completely filled or completely empty, (b) in a semiconductor, both bands are partially filled, and in a metal, (c) the Fermi level resides within one of the bands, or (d) E_V is above E_C so that there is no energy gap. In (d), the E_F can be in any position.

rectifying characteristics. Examples are the tunnel diode and the Gunn diode. A more proper definition for a diode now is simply a two-terminal device having nonlinear DC characteristics.[2] Rectifiers are therefore only a subgroup of diodes. Another subgroup of diodes that are distinctively different from rectifiers are those having negative differential resistance. Within this group of negative-resistance devices, there are two types: one that has a negative dI/dV region, and the transit-time devices where the negative resistance is due to the small-signal current and voltage that are out of phase.

A switch, in semiconductor terms, is a device that has two states–a low-impedance state (on) and a high-impedance state (off). Switching between these two states can be controlled by voltage, current, temperature, or by a third terminal. A transistor, for example, is considered a three-terminal switch in digital circuits. Thyristors are also a special case of switch. They are included in a separate group from switches because they usually contain *p-n-p-n* layers, have more than two terminals, and are used mainly as power devices.

Unlike diode, transistor (transfer-resistor) was a new name coined at the beginning of the semiconductor era for the bipolar transistor, instead of keeping the old equivalent of triode. In the classification of devices, this book does not follow the common approach in literature to divide devices into bipolar and unipolar types. For transistors, the bipolar transistor has been used as a representative of the first type, and MOSFET and JFET of the second type. The reason behind that classification is for a bipolar transistor, the base current is due to one type of carrier while the emitter-collector current is of the opposite type; thus, both types of carriers are involved. For a MOSFET, the gate current is negligible, and the carriers in the channel are the only kind responsible for the current flow. The author, however, feels that the classification based on this

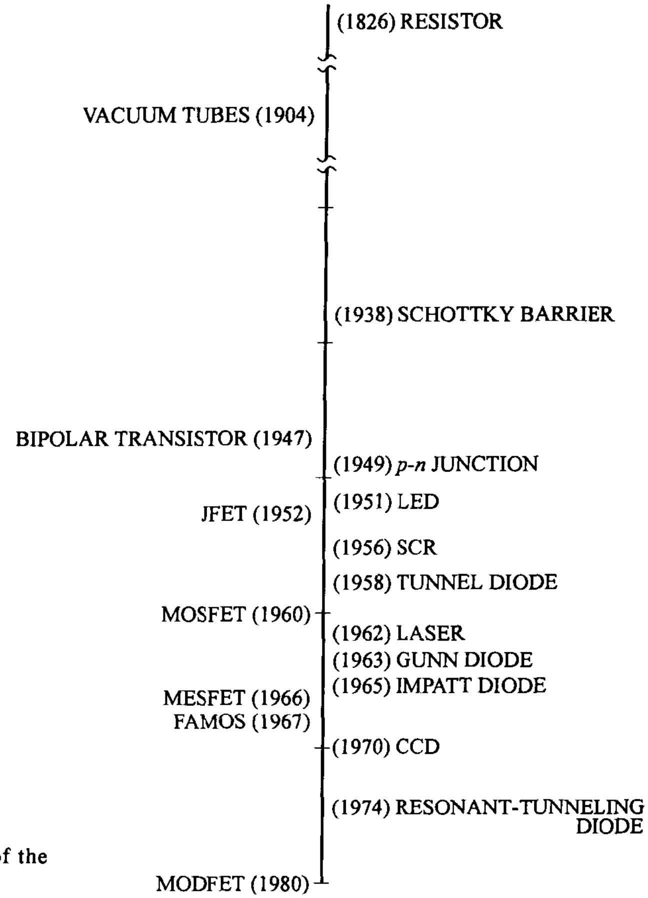

FIGURE I.3
Some major milestones of the electronics industry.

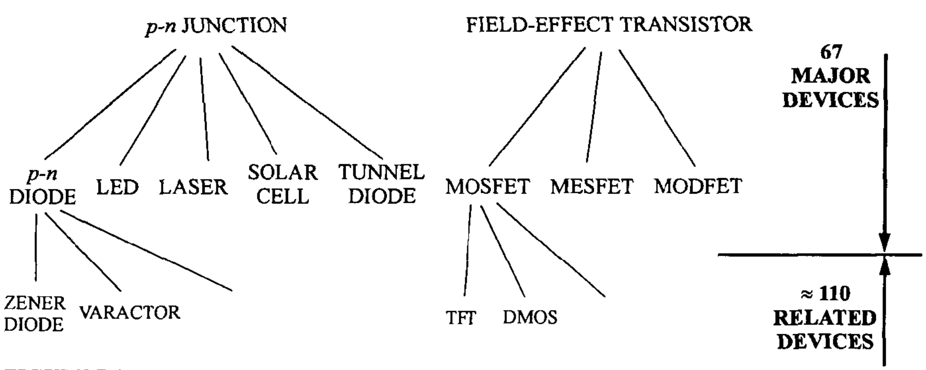

FIGURE I.4
Hierarchy of semiconductor devices. Major devices are included in individual chapters, and their variations are included as "related devices."

bipolar-unipolar terminology is not clear, or maybe even incorrect. For example, in a bipolar transistor, the base current is a sort of leakage current. It is only a by-product of a base potential needed to modulate the emitter-collector current. If this base current is somehow made zero, the bipolar transistor would still work, and work even better. In fact, the main purpose of a heterojunction bipolar transistor is to suppress this base current, without affecting the main current. Next, let us consider an enhancement JFET. To turn the transistor on, the *p-n* junction gate is forward biased. This injects minority carriers into the channel. The JFET is therefore as "bipolar" as the bipolar transistor. This argument can also be extended to diodes. A *p-n* junction has been referred to as a bipolar device while a Schottky barrier as a unipolar device. For practical *p-n* junctions, they are usually one-sided in that one side is much more heavily doped than the other. A typical Si *p-n* junction has doping levels of 10^{20} cm^{-3} and 10^{16} cm^{-3}, and the ratio of the two types of current is $\approx 10^{-4}$. For a practical Schottky-barrier diode, even though the current is dominated by majority carriers, the minority-carrier current is not zero. It is a factor of $\approx 10^{-4}$–10^{-6} (injection efficiency) smaller. As seen from these diodes, the transition from a bipolar device to a unipolar device is not clear.

In this book, transistors are divided into three groups, following the notation used in Ref. 3. These are (1) field-effect transistor (FET), (2) potential-effect transistor (PET), and (3) hot-electron transistor (HET). The field effect is defined, originally by Shockley when the first field-effect transistor (JFET) was envisaged, as "modulation of a conducting channel by electric fields."[4] An FET differs from a PET in that its channel is coupled capacitively by transverse electric fields while in a PET, the channel's potential is accessed by a direct contact.* This distinction is illustrated in Fig. I.5. The capacitive coupling in an FET is via an insulator or a space-charge layer. A hot-electron transistor is a special case of PET, whose emitter-base junction is a heterostructure such that the emitted carriers in the base have high potential or kinetic energy (Fig. I.5(e)). Since a hot carrier has high velocity, HETs are expected to have higher intrinsic speed, higher current, and higher transconductance. One also notes that the energy-band diagrams of the FET and the PET (excluding HETs) are similar. This is because the way the channel is influenced, either capacitively for FET or directly for PET, is not indicated in these diagrams. One observation on FETs is that almost all have channel conduction by the drift process, and have a well-defined threshold voltage.

To achieve the goal of including this large variety of devices as a guide, a special format is created. First, each chapter is dedicated to one device only. The chapters are written to be independent, and readers can go directly to the intended

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* FET and PET are defined in Ref. 3 differently by the editor (S. Sze) and by one of the contributors (S. Luryi). Sze's definition (pp. 3 and 6 in Ref. 3), adopted in this book, is based on the physical structure, while Luryi's definition (p. 400 in Ref. 3) is based on the current-control mechanism. In the latter definition, the same device can switch from an FET to a PET, depending on the bias regime.

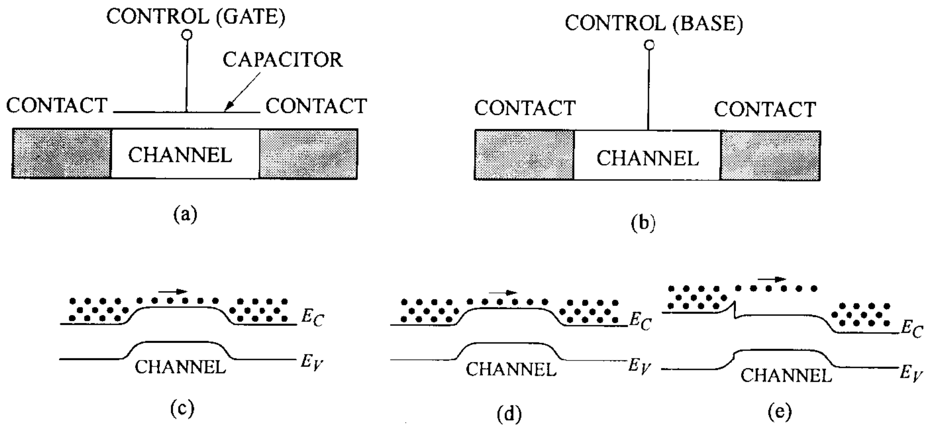

FIGURE I.5
Schematic structures of (a) FET and (b) PET. Energy-band diagrams of n-channel (c) FET, (d) PET, and (e) HET. Note that (c) and (d) are similar. HET is a special case of PET.

device to get an overview quickly by reading only a few pages. Second, each chapter consists of four main sections:

1. History
2. Structure
3. Characteristics
4. Applications

With these, the essential information about each device is given: When was it invented and by whom? (History) How is it made? (Structure) How does it work? (Characteristics) What is it for? (Applications) For more than half of the chapters, there is another section–5. Related Devices, to cover slightly different structures. This is necessary to account for all devices to meet the goal of completeness and yet not have more than the existing 67 chapters. This book is intended to be an engineering approach to understand semiconductor devices, giving a pragmatic overview. Because of its complete coverage, readers can also pick up the subtle differences that sometimes exist between devices. With this rigid format, the listing of sections .1–.4 are omitted from the Contents to avoid repetition in every chapter, with the exception of Chapter 1 as an example. In effect, only the device names are listed in the Contents.

The appendixes are extensive compared to those in other semiconductor-device books. Appendix A includes some non-semiconductor devices that one might encounter in this broad field. Appendix B covers the device physics and phenomena that are common to some devices, to avoid repetition. This appendix also makes up the lost opportunity in this book format to go over some

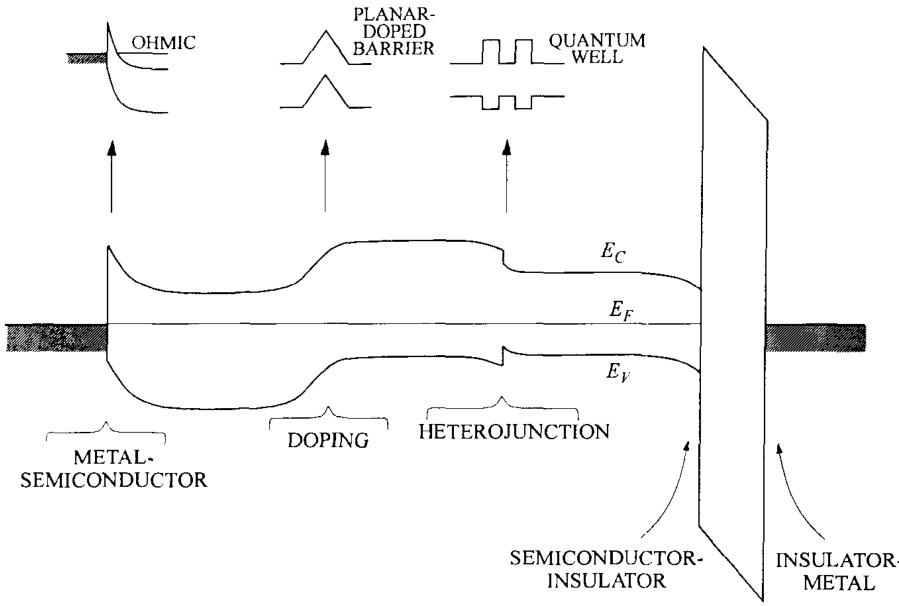

FIGURE I.6
Energy-band diagrams showing the basic device building blocks, or interfaces. Inserts indicate that ohmic contact, planar-doped barrier, and quantum well are special cases of Schottky barrier, doping interface, and heterojunction, respectively.

fundamental device physics. Appendix C covers the general applications of various device groups, again to avoid repetition in some chapters. Appendixes D and E are the more typical kind of semiconductor data and background information, but attempts have been made to collect as much information needed for a stand-alone handbook.

In the course of writing this book, several thoughts arose that are worth mentioning. Semiconductor devices can be viewed as consisting of device building blocks. In spite of the large number of devices, there are only a few building blocks, which are interfaces of two materials or doping types. These fundamental interfaces are all included in the energy-band diagram of the book cover, repeated here in Fig. I.6. They are, from left to right, a metal-semiconductor interface, doping interface, heterojunction, semiconductor-insulator interface, and an insulator-metal interface. The metal-semiconductor interface, known as the Schottky barrier, also includes the ohmic contact which is inevitable in every semiconductor device. The doping interface also includes the planar-doped barrier. The heterojunction is also the basis for quantum-well devices. A bipolar transistor, for example, is built of two *p-n* junctions. A