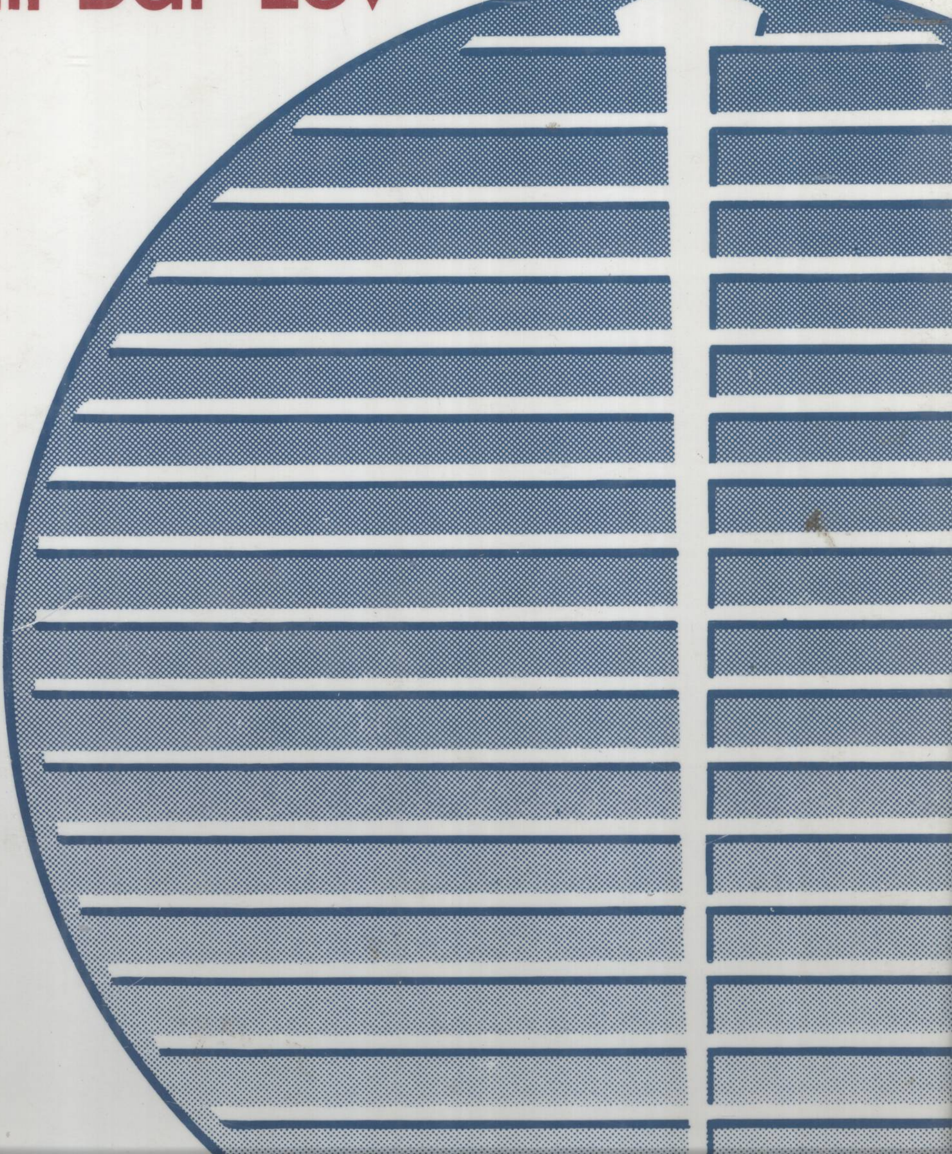
SEMICONDUCTORS AND ELECTRONIC DEVICES 2nd EDITION

Adir Bar-Lev



SEMICONDUCTORS AND ELECTRONIC DEVICES
2nd Edition

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PREFACE

We live in a period in which a thorough knowledge of semiconductor devices in their various forms has become essential for all students majoring in electronic and applied physics. Present day devices, however, are no longer just diodes or transistors but are either large scale integrated circuits or special purpose components whose design and performance are intimately connected with their physics and processing.

There are many books covering semiconductor physics, others that cover fundamental devices, such as diodes and transistors, and others still that handle basic integrated circuits and their processing. There are far fewer books which try to combine those interrelated subjects, and fewer still which succeed in doing so without becoming too cumbersome or falling apart at the junction between the physics and engineering parts.

Most of these books concentrate on one part at the expense of the other, sometimes giving a great deal of background physics which is not applied in the sections on devices, and sometimes going more deeply into properties of materials and technology than is necessary for the systems-oriented student. This textbook, intended for both electronic and applied physics undergraduates who aim to work in or with solid state devices, tries to avoid these pitfalls.

For the future electronic engineer, it is no longer enough to study the terminal electrical characteristics of the semiconductor device while treating the device itself as a 'black box'. Most of the sophistication of modern electronics is hidden in that box, and more and more engineering and scientific effort will be required for work in device development, design, simulation, production and testing in the future. The devices in fact become subsystems, ready for the use of the systems engineer. Even he, the user of the devices, will not be able to get the most out of them or contribute towards design of more advanced ones without a good knowledge of the principles underlying their operation and the technology used in manufacturing them.

This book is intended to provide the fundamental step in the education of young engineering students who intend either to specialize in semiconductor devices or to be mainly a user of them. The former may later specialize in the technology of microelectronics, integrated circuit design or special semiconductor devices. The latter will gain a broad enough knowledge of semiconductors, devices and basic integrated circuit approaches to tackle them with confidence in their future courses on electronic circuits and systems.

In a complementary way, physics students who intend to specialize in semiconductors will gain from this book an understanding of both discrete and integrated circuit devices, the relationship between their physical and electrical properties and the way they function in the electronic system. They will learn to see the subject from the viewpoints of the device designer, tester and user, to complement their future and more extensive courses in solid state physics.

It is the purpose of the 2nd edition to lead the electronics or physics major from basic semiconductor physical concepts into the world of VLSI circuits and of other sophisticated components, a world in which device requirements are no longer stated only in terms of transistor betas or breakdown voltages but also in terms of propagation delays and noise margins.

SI units are used throughout, with the addition of the centimeter and electron-volt to conform with their universal use in the semiconductor industry and market.

The prerequisites for this book are, from the mathematical side: some knowledge of differential and integral calculus and first- and second-order differential equations. On the physical side, some knowledge of modern physics and statistical thermodynamics will be helpful. However, a short summary of the necessary physics is given whenever necessary. The background requirement from electrical engineering is basic electrical network analysis under d.c., a.c. and transient conditions.

Since, in this book the student meets for the first time a host of new terms and ideas which he or she must learn to recognize and use, these terms and ideas are introduced gradually, sometimes in two stages, and physical clarity is preferred to full and rigorous mathematical treatment. The authors experience in teaching this course for several years in the Technion, Israel Institute of Technology has led him to believe that, in a fundamental course such as this, mathematics should be used only to clarify the physical picture and provide tools for the student laboratory work, and should be avoided if it becomes so complicated that most of the student effort is diverted into following it. The place for the more advanced and rigorous treatment is in specialized graduate courses, which may follow this one, when the student has already mastered and understood how and why things work. For the same reason this book is not cluttered with too many references and bibliographies. However, following each important topic covered, the student is referred to one or two books or review papers which can be used for broader coverage of that topic.

The book has essentially four parts:

1. *Semiconductor materials and physics.* Here the student is led towards the electrical properties of semiconductors. This part is composed of Chapters 1–7 and is given on a basic level suitable for the general electrical student, and can be considered only as an introduction for a physicist wanting to specialize in semiconductor physics. It reviews methods for preparation of semiconductor materials, describes crystal structure,

defines the important electrical parameters: mobility, conductance, diffusion constant and life time. Methods for their measurements are then described. The simple valence model is used first because it is easier for the student to grasp intuitively, makes possible quantitative treatment at an early stage and leads the student gradually to the more complex energy-band theory based on quantum mechanics through the Kronig–Penney model. The density of states in the bands is then found and the probability of their occupation by current carriers is calculated. This leads to the concept of Fermi level, and the homogenous intrinsic and extrinsic semiconductor cases. Only that part of solid state physics that is essential for understanding semiconductor device operation is included.

2. *Basic devices.* This part is composed of Chapters 8, 9, and 11 to 15. It starts with PN junction properties (including generation–recombination currents and heterojunctions) and continues to analyze all the important classes of basic devices, such as the various kinds of diodes, MOS, JFET and bipolar transistors. The small and large signal models are developed and deviations of real devices from their idealized models is discussed, together with the dependence of the model parameters on operating point, ambient conditions or frequency. Examples are then given of the use of such models in analyzing elementary circuits. Although electronic circuits as such are outside the scope of this book, the author feels that understanding of such basic ideas as amplification, load line, frequency response or switching times is essential for understanding integrated circuit building blocks. These are covered in Chapter 13, following the first active device family described, the FETs.

3. *Integrated circuit devices and processes.* This part starts with Chapter 16 describing the various major technologies in use today in semiconductor manufacturing. Knowledge of such processes helps in understanding the limitations of devices, the yields and parameter spread expected of various device families and other differences between them. Chapter 17 covers bipolar ICs, including such topics as design philosophy and fundamental building blocks for analog and for digital applications. Chapter 18 is dedicated to MOS ICs (NMOS, CMOS, static and dynamic gates, CCDs and memory cells) together with a discussion of the VLSI era and related problems, such as scaling or large area photolithography.

4. *Special semiconductor devices.* This part is based on parts 1 and 2 and is independent of 3. It includes optoelectronic devices (Chapter 10) introduced early so that student interest is boosted by applying their already accumulated knowledge to a modern, real life field. It continues in Chapters 19 and 20 which deal with power semiconductor devices (thyristors, bipolars, vertical MOST and the static induction transistor) and microwave devices (bipolars, varactors, transferred electron and impatts) respectively. This part ends with Chapter 21 which looks at devices and technologies of the future, subjects that are still in developmental stages or just entering into use.

Four appendices close the book. The first sums up the subject of the various two-part representations and their interrelationships. The method and equations developed are useful for working with equivalent circuits. The second covers the fundamentals of thermionic emission and vacuum tubes. Triodes and their small-signal models, limitations, and short descriptions of the cathode ray tube and photomultiplier are included. The third lists important and useful physical constants and semiconductor material properties and the last gives silicon processing data necessary for working out problems related to diffusions or implantations.

Each chapter is followed by a list of questions to test the reader's grasp of the various ideas outlined in the chapter, and then by a list of problems to train the reader in applying the mathematical approaches and equations. Some of the problems actually supplement and broaden the information previously given.

To cover all the material a two-semester course is necessary in which the chapters composing parts 1 and 2 are covered in the first one and may be looked upon as a basic course, while parts 3 and 4 may be considered a more advanced course and covered in the second one. As already mentioned, parts 3 and 4 are independent of one another and the teacher may elect to cover only selected chapters from them.

A teacher's manual containing the solutions to the problems can be obtained from the publisher.

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A. B-L.

CONTENTS

SEMICONDUCTORS AND THEIR PREPARATION FOR ENGINEERING USE 1

1.1 Semiconductors

Semiconductor materials are distinguished by having their specific electrical conductivity somewhere between that of good conductors (10^6 $(\Omega cm)^{-1}$) and that of good insulators ($10^{-5}(\Omega cm)^{-1}$); hence the name. Among those materials, by far the most important in engineering use is silicon (Si). Of quite lesser importance is germanium (Ge), which, like silicon, is an element belonging to Group IV of the periodic table (Table 2.2). Becoming more important daily are the compound semiconductors, usually compounded of two elements (but sometimes more) of Groups III and V or II and VI of the periodic table. From those gallium arsenide (GaAs) is the most important. Also in use for specific purposes are indium antimonide (InSb), gallium phosphide (GaP), cadmium sulphide (CdS), lead–tin–telluride (PbSnTe) and others.

We shall mainly concentrate on Si, Ge and GaAs, from which the majority of present-day devices are being made, but the theoretical results apply to all of them.

Electronic devices necessitate use of almost absolutely pure semiconductor materials in which an exactly measured amount, usually extremely small, of a foreign dopant has been included to control its electrical properties. Also, the semiconductor must normally be in the form of a single crystal throughout the device, since, as we shall see, its desired electrical properties depend on the ordered, periodic nature of the crystal structure and any faults would be detrimental.

Let us give a short review of present-day engineering solutions to the purity and single crystal requirements.

1.2 Purification

Silicon, one of the most abundant elements on earth, is always found in a compound form in nature, usually combined with oxygen (sand is mainly SiO_2). It is first purified as far as possible by chemical methods. Reduction with carbon, according to $SiO_2+2C \rightarrow Si+2CO$, yields metallurgical grade silicon of up to 99% purity. By combining it with HCl, it is converted to liquid $SiHCl_3$. This is further purified using fractionation processes similar to those employed in the petroleum industry, and then reduced in hydrogen according to $SiHCl_3+H_2 \rightarrow Si+3HCl$ and vapor deposited on thin silicon rods used as hot substrates. The deposition forms thick, semiconductor grade, polysilicon rods in which the concentration of troublesome impurities is about 1 in 10^9 silicon atoms. In single crystal form such silicon would have a resistivity of about 200 Ωcm which is sufficient for most applications. For special uses very high purity (and consequently resistivity) Si is needed. This is obtained by a method called zone refining, also used for germanium. It is based on the tendency of most impurities to remain in the liquid part when the melted semiconductor gradually solidifies. The ratio of the impurity concentration on the solid side of the liquid–solid interface C_s to that on the liquid side C_l is called the *segregation* (or distribution) coefficient K of that specific impurity and is usually much smaller than one.

Figure 1.1(a) describes such a purification system for Si using a floating zone; a solid Si bar is held vertically inside a fused silica (also called quartz) tube without touching it. (This is important, since melted Si, at 1420°C, is extremely active chemically and combines with or sticks to everything it touches.) Surrounding the tube there is a short copper coil in which a high-frequency current (about 0.5 MHz) passes, generated by an induction heating generator. Strong eddy currents are induced in the section of the Si bar inside the coil and this section melts. If this section is short, the strong surface tension of molten Si, combined with its low density, is sufficient to support the molten zone in its place. The quartz tube, being an insulator, is not affected.

The coil is slowly moved vertically relative to the Si, with the region immediately in front of it melting and that behind it solidifying. Because of the small segregation coefficient, most impurities stay in the melt and are therefore 'swept' along the bar towards one end. This may be repeated several times, the relatively dirty edge sawn off, the remainder recast into a new bar and the whole process repeated. A very high degree of purity results, with the remaining undesired impurity concentrations ten orders of magnitude or more below that of the Si. The zone refining is usually done in a hydrogen atmosphere to reduce the oxygen content. Germanium can be zone refined in horizontal graphite boats as it is much less active at its melting temperature of 937°C.

It can easily be shown (Problem 1.4) that if the original impurity concentration C_0 in the semiconductor is uniform, then, after a single molten zone

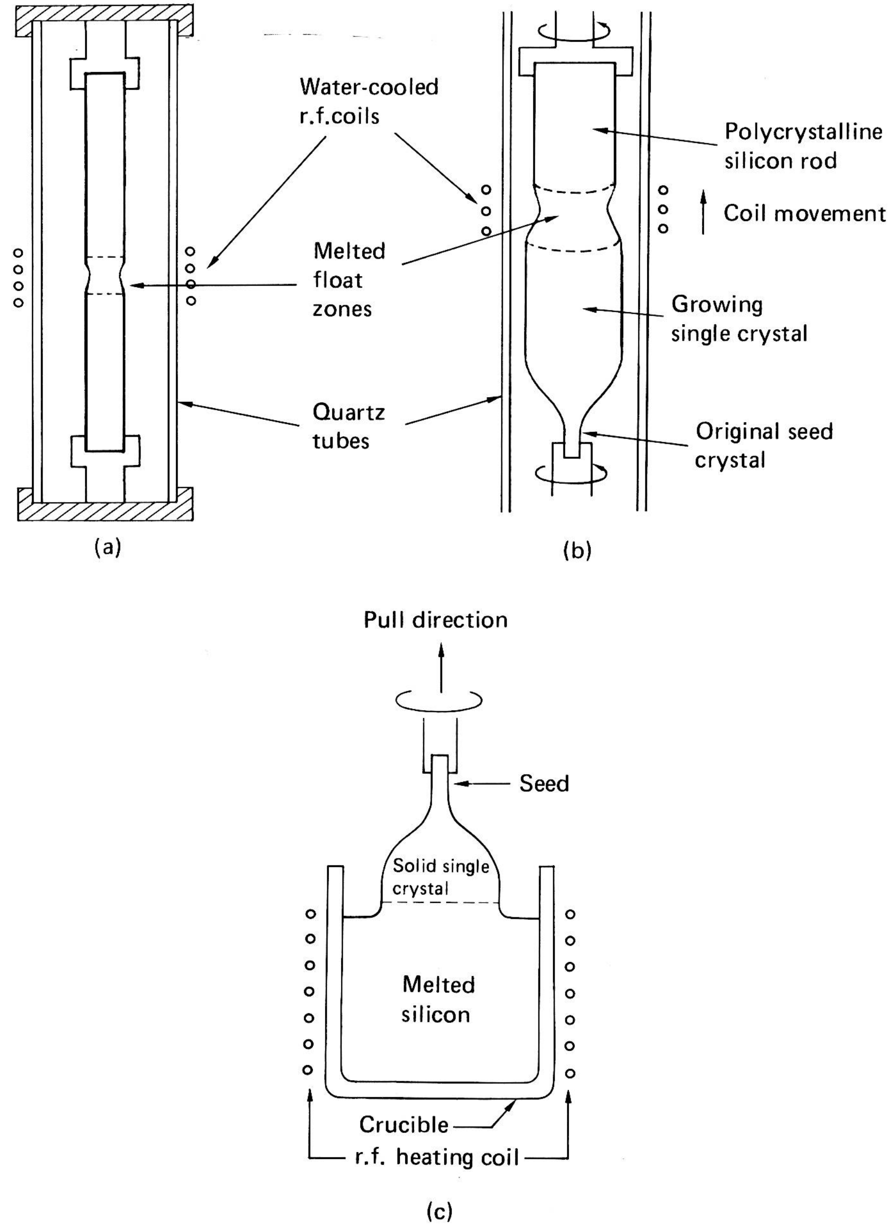

Figure 1.1. (a) Float zone (FZ) purification of Si; (b) single crystal growth by FZ technique; (c) the Czochralski single crystal pulling technique.

pass starting at $x=0$, one gets a new impurity concentration profile of

$$C_s(x) = C_0[1-(1-K)e^{-Kx/L}], \quad (1.1)$$

where L is the length of the molten zone.

This equation is the initial impurity distribution for the second pass. For copper ($K=4\times10^{-4}$) or iron ($K=8\times10^{-6}$), e.g., only a few passes suffice to appreciably reduce the impurity content.

1.3 Single-crystal Formation

Conversion of the polysilicon rods to single crystal may be done by a similar float zone technique shown in Fig. 1.1(b). The polyrod is mounted vertically over a piece of single crystal, Si, called *the seed*, that is pre-cut in the desired crystallographic orientation. RF heating is used to melt the top of the seed and the bottom of the polyrod and form a molten float zone. If the RF coil is now moved very slowly upwards, the bottom of the molten zone would start to solidify on top of the seed, continuing its single crystal structure and orientation. As the molten zone traverses the polyrod, it transforms the rod's polycrystalline structure into a single crystal.

Both rod and seed are slowly rotated during growth to preserve uniformity of temperature and composition. Crystals of 10 cm diameter and 50 cm long are grown routinely today.

The most common method for silicon crystal growing in use today is the Czochralski pulling technique. The purified Si is remelted in a quartz-lined graphite crucible, shown schematically in Fig. 1.1(c). The *seed*, attached to a holder, is dipped into the molten Si and then very slowly pulled up again, turning at the same time to preserve uniformity. Molten Si sticking to the seed will start to solidify, if the temperature is properly controlled, and its crystal structure will follow that of the seed. The growth is performed with the growing crystal containing an exactly known amount of some specific impurity previously added to the melt, which, as we shall see, determines the electrical properties. Long crystals of 10 and 12.5 cm diameter can be grown.

Since Si in molten form is chemically very reactive, Czochralski (CZ) pulled crystals are not as pure as FZ grown ones and contain some undesired impurities, like carbon and oxygen, absorbed from the crucible and its lining, and sometimes even minute traces of heavy metals. As we shall learn, this affects the electrical properties of devices built in such a crystal.

Compound semiconductors are much more difficult to grow in single crystal bulk form. The difficulties stem from the usually very different vapor pressures of the compound constituents causing the more volatile one to evaporate away from the melt.