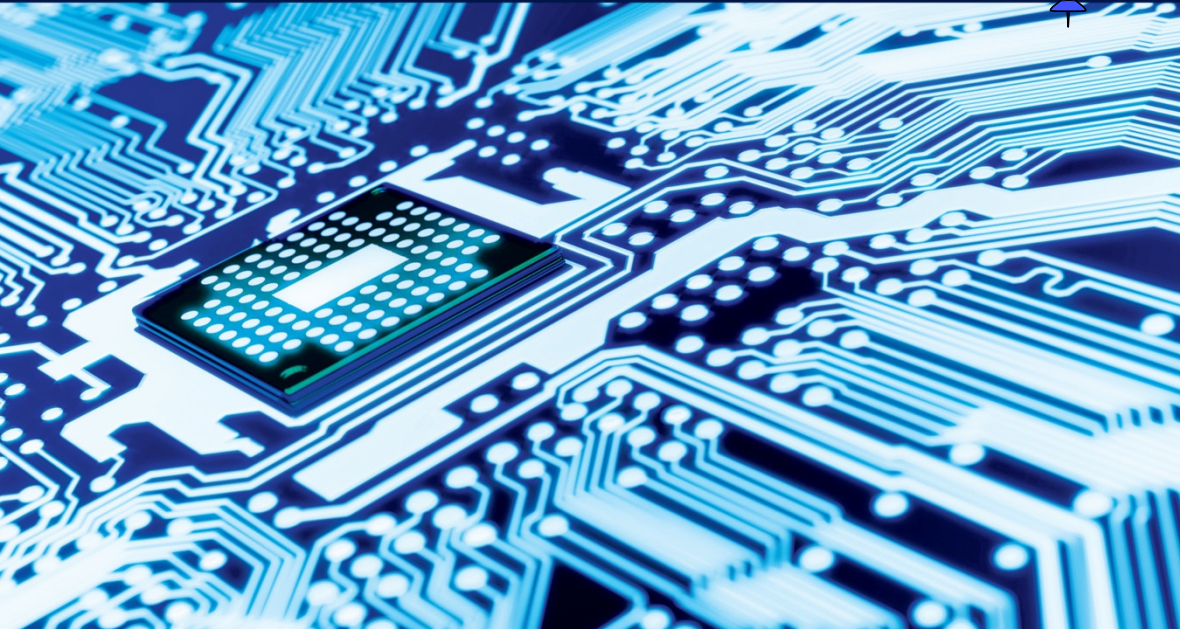


ELECTRONICS ENGINEERING SERIES



Fundamentals of Electronics 1

*Electronic Components
and Elementary Functions*

Pierre Muret

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First published 2017 in Great Britain and the United States by ISTE Ltd and John Wiley & Sons, Inc.

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Hoboken, NJ 07030
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Library of Congress Control Number: 2017944816

British Library Cataloguing-in-Publication Data
A CIP record for this book is available from the British Library
ISBN 978-1-78630-181-9

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Preface

Today, we can consider electronics to be a subject derived from both the theoretical advances achieved during the 20th Century in areas comprising the modeling and conception of components, circuits, signals and systems, together with the tremendous development attained in integrated circuit technology. However, such development led to something of a knowledge diaspora that this work will attempt to contravene by collecting both the general principles at the center of all electronic systems and components, together with the synthesis and analysis methods required to describe and understand these components and subcomponents. The work is divided into three volumes. Each volume follows one guiding principle from which various concepts flow. Accordingly, Volume 1 addresses the physics of semiconductor components and the consequences thereof, that is, the relations between component properties and electrical models. Volume 2 addresses continuous time systems, initially adopting a general approach in Chapter 1, followed by a review of the highly involved subject of quadripoles in Chapter 2. Volume 3 is devoted to discrete-time and/or quantized level systems. The former, also known as sampled systems, which can either be analog or digital, are studied in Chapter 1, while the latter, conversion systems, we address in Chapter 2. The chapter headings are indicated in the following general outline.

Each chapter is paired with exercises and detailed corrections, with two objectives. First, these exercises help illustrate the general principles addressed in the course, proposing new application layouts and showing how theory can be implemented to assess their properties. Second, the exercises act as extensions of the course, illustrating circuits that may have been described briefly, but whose properties have not been studied in detail. The

first volume should be accessible to students with a scientific literacy corresponding to the first 2 years of university education, allowing them to acquire the level of understanding required for the third year of their electronics degree. The level of comprehension required for the following two volumes is that of students on a master's degree program or enrolled in engineering school.

In summary, electronics, as presented in this book, is an engineering science that concerns the modeling of components and systems from their physical properties to their established function, allowing for the transformation of electrical signals and information processing. Here, the various items are summarized along with their properties to help readers follow the broader direction of their organization and thereby avoid fragmentation and overlap. The representation of signals is treated in a balanced manner, which means that the spectral aspect is given its proper place, to do otherwise would have been outmoded and against the grain of modern electronics, since now a wide range of problems are initially addressed according to criteria concerning frequency response, bandwidth and signal spectrum modification. This should by no means overshadow the application of electrokinetic laws, which remains a necessary first step since electronics remains fundamentally concerned with electric circuits. Concepts related to radio-frequency circuits are not given special treatment here, but can be found in several chapters. Since the summary of logical circuits involves digital electronics and industrial computing, the part treated here is limited to logical functions that may be useful in binary numbers computing and elementary sequencing. The author hopes that this work contributes to a broad foundation for the analysis, modeling and synthesis of most active and passive circuits in electronics, giving readers a good start to begin the development and simulation of integrated circuits.

Outline

- 1) Volume 1: Electronic components and elementary functions.
 - i) Diodes and applications
 - ii) Bipolar transistors and applications
 - iii) Field effect transistor and applications
 - iv) Amplifiers, comparators and other analog circuits

2) Volume 2: Continuous-time signals and systems [MUR 17a].

i) Continuous-time stationary systems: General properties, feedback, stability, oscillators

ii) Continuous-time linear and stationary systems: Two-port networks, filtering and analog filter synthesis

3) Volume 3: Discrete-time signals and systems and conversion systems [MUR 17b].

i) Discrete-time signals: Sampling, filtering and phase control, frequency control circuits

ii) Quantized level systems: Digital-to-analog and analog-to-digital conversions

Pierre MURET
June 2017

Introduction

In this first volume, we address the physics of semiconductor devices directly through electrostatics and the laws steering the transport of charge carriers. This allows us to broach the governing principles at work in semiconductor electric components, which are described and quantified in order to expose the relations that control external electric quantities. Through the first three chapters, devoted, respectively, to diodes, bipolar transistors and field effect transistors, the electrical characteristics of these components can be deduced and expressed as electric models. We then consider the static or instantaneous voltages and currents present in these nonlinear or linear electric models to obtain the properties of active circuits made using these components and passive elements. In some cases, these considerations will require students to solve first-order differential equations or use complex impedance and transmittance to represent values in sinusoidal conditions (see Appendix).

Each chapter emphasizes the applications derived from these models, in terms of analog and logical functions, a majority of which are based on the original nonlinearity of the components. Conversely, linearized models become useful mainly from Chapter 2 onwards, to help with in-depth analysis of the amplifier circuits, and in particular for the operational amplifiers in Chapter 4. In this volume, the study of signal representations is kept to a strict minimum, largely confined to the Appendix, with the exception of the noise problem in amplifiers in Chapter 4. The content of the Appendix should be of use for the wider public who may be unfamiliar with

the laws and theorems of electrokinetics, which are indispensable in this volume covering a variety of electronic circuits and equivalent component circuits. Exercises allow a deeper analysis of fundamental layouts comprising a small number of active devices, typically from two to 10.

Diodes and Applications

1.1. Semiconductor physics and current transport in pn diodes

1.1.1. Energy and concentration of mobile charge carriers (electrons and holes)

Studies of electrons' physical properties indicate that they appear either as particles with a movement quantity (or impulse) of p and mass m , or as waves of wavelength λ and wave vector k . Between these values, De Broglie's wave mechanics establishes the following relation: $p = \hbar k = \frac{h}{\lambda}$, where $h = 6.62 \times 10^{-34}$ J·s and $\hbar = h / 2\pi$.

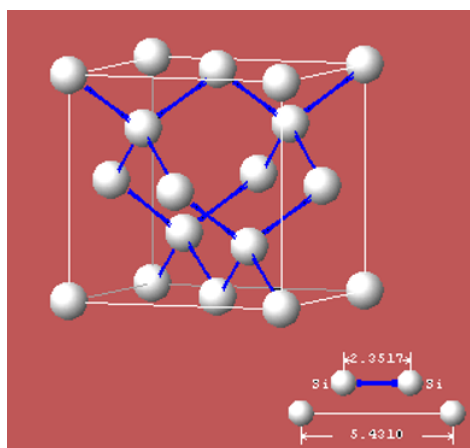


Figure 1.1. Silicon crystal lattice (Ångstrom distances, equal to 0.1 nm)

Here, kinetic energy is $E_c = \frac{p^2}{2m}$, while potential energy corresponds to the work of the attractive force between 1 electron and 1 proton until they are approximately separated by the atomic radius, that is $a_0 \approx 0.2$ nm; therefore, $U = \int_{a_0}^{\infty} \frac{e^2}{4\pi\epsilon r^2} dr = \frac{e^2}{4\pi\epsilon a_0}$ (with $e = 1.6 \times 10^{-19}$ Coulomb and $\epsilon \approx 10^{-10}$ Farad/m in a semiconductor such as Si) to the order of 10^{-19} J, or a little less than 1 eV.

In an isolated atom, quantum mechanics makes a connection between energy and the wave frequency associated with each electron, so that the energy of each can only take certain values known as energy levels. When the atoms are in a solid such as silicon, which can hold a crystal shape where atoms are arranged in a regular and periodic manner in space (Figure 1.1), the potential in terms of the electrons is that determined by the atoms' nuclei as well as other electrons, also becoming regular and periodic in space.

A consequence of this is the transformation of energy levels into allowed energy bands separated by a forbidden bandgap (Figure 1.2). These allowed bands are made up of as many energy levels as there are electrons in the solid, also known as energy states or quantum states, spread over an energy range of several electron volts.

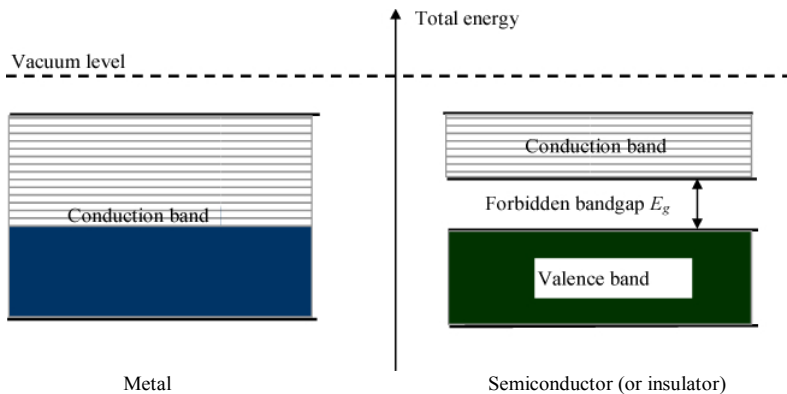


Figure 1.2. Energy bands of a solid (full and empty quantum states in dark and hatched color, respectively)

Only a single electron can be placed in the allowed bands per quantum state, both for isolated atoms and in solids.

Conduction is only possible if electrons can change quantum state, as this allows them to acquire kinetic energy and movement. This change can occur in the case of metals, as the allowed band with the highest energy levels, known as the conduction band, is only ever partially filled; conversely, this can only occur when the temperature increases above absolute zero in semiconductors, since the forbidden band separates a full valence band from an empty conduction band at absolute zero. This is because thermal excitation induces the transfer of some electrons from the valence band into the conduction band. In the case of semiconductors, statistics show that the product of electron concentration n in the conduction band and of holes p (that is the absence of electrons that may be considered as positively charged particles with a positive mass) in the valence band is equal to the square of the intrinsic concentration n_i :

$$n.p = n_i^2 = N_c N_v \exp(-E_g/kT)$$

where E_g = width of the forbidden bandgap, k = Boltzmann constant = 1.38×10^{-23} J/K and N_c, N_v = density of effective state in the conduction and valence bands (m^{-3}) so that $N_c N_v = B T^3$ (T in $^\circ\text{K}$ and B to the order of $5 \times 10^{43} \text{ m}^{-6} \text{ K}^{-3}$ for silicon).

Solids with semiconductor characteristics are chiefly those whose atoms have 4 electrons on their peripheral layer, that is those in column IV of the periodic table ($2s^2 2p^2$ configuration for diamond, $3s^2 3p^2$ for silicon, $4s^2 4p^2$ for germanium, or mixed for SiC) or also those made up of atoms from columns III and V (called III–V, such as GaAs, GaP, InP, InAs, GaN, AlN and InN) or columns II and VI (called II–VI, such as ZnO, ZnSe, CdTe, CdS and ZnTe).

Accordingly, we can only consider the peripheral electrons, of which there are on average 4 per atom, whose charge is balanced by four nucleus protons (either 3 and 5, or 2 and 6 for materials III–V and II–VI, respectively).

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
1 H												II	III	IV	V	VI	VII	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne	
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar	
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	

Figure 1.3. Periodic table of elements

In intrinsic semiconductors, that is ideally without any impurities, there are as many holes as electrons, such that $n = p = n_i$, the density of intrinsic carriers, since an excited electron in the conduction band automatically leaves a hole in the valence band (Figure 1.4).

This situation is modified by doping, which corresponds to the introduction of foreign atoms, also known as impurities. Doped semiconductors are far more useful, since we can favor either conduction by electrons or conduction by holes. The relation $n \cdot p = n_i^2$ still applies, however:

- for n doping of semiconductors IV-IV: $n = N_D \gg p$ by introducing atoms located in a column further to the right, which then become a concentration of N_D donors;
- for p doping of semiconductors IV-IV: $p = N_A \gg n$ by introducing atoms located in a column further to the left, which then become a concentration of N_A acceptors. For III–V and II–VI, doping occurs along the same lines, that is by increasing or decreasing the number of nucleus protons by one unit with the impurity relative to the atom that is being replaced.

By means of doped semiconductors (Figure 1.5), we can obtain zones with localized charges (ionized donors or acceptors) if the mobile carriers (electrons or holes) have been carried into another zone of the component by an electric field.

The combination of several such zones, known as space-charge zones or more commonly, depleted zones, also allows us to obtain this electric field and create components. Moreover, a p type zone in contact with an n type

zone forms a pn diode. The asymmetry of fixed charges in both zones leads to asymmetry of electrical characteristics and the rectification effect.

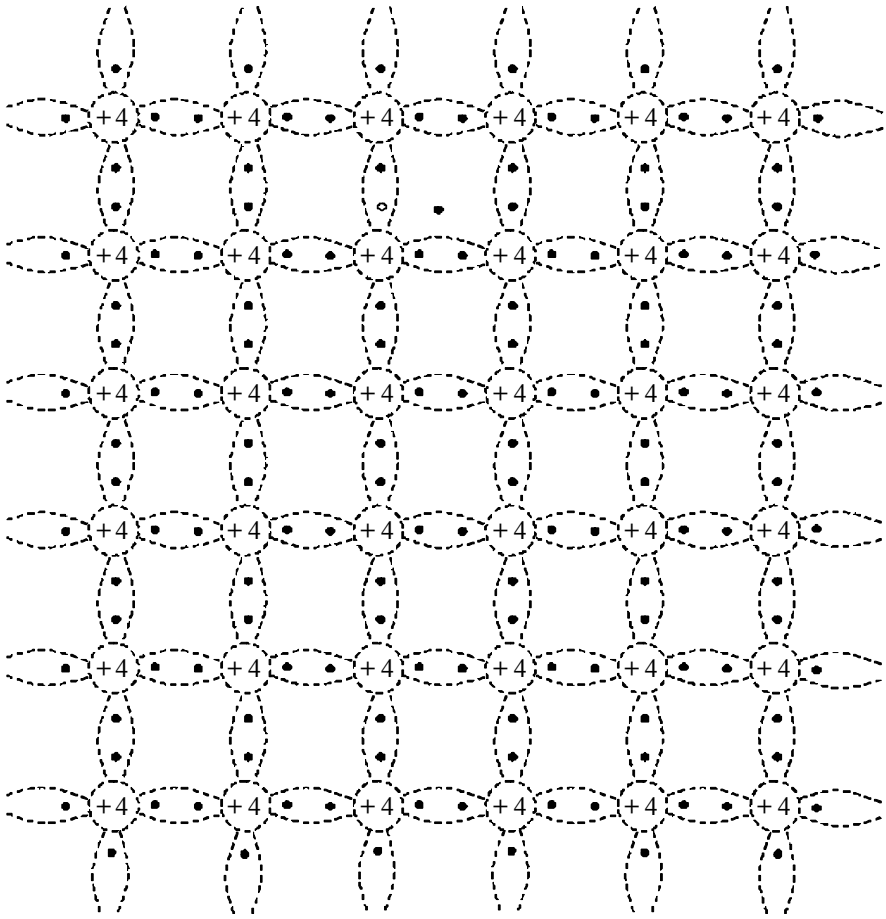


Figure 1.4. *Flattened structure of a doped intrinsic covalent semiconductor (electrons represented by a full black circle, holes by a hollow black circle)*

The fixed charges that remain in a depletion zone after the departure of electrons are positive due to the surplus positive charge ($5+$ on the proton and $4-$ for the peripheral electrons) on the nucleus of ionized donors. On the other hand, the fixed charges that remain in a type p depletion zone after the departure of holes are negative due to the electron that has taken the place of the hole when it leaves the ionized acceptor ($3+$ on the proton and $4-$ for the