ELECTRONIC DEVICES

A University text book

ABDELHALIM ZEKRY

Professor of Electronics

Faculty of Engineering,

Ain Shams University

Diagrams & word-processing
Modern Center for Computing, ✆ 4829975

Dar El Hakeem Press, Cairo

1998

PREFACE

The electronic systems and equipment such as radio transmitters, radio receivers, electronic exchangers, digital computers, ...etc., are generally composed of electronic circuits. Each circuit performs a predetermined function in the electronic system. Besides the conventional passive circuit elements, an electronic circuit contains electron devices.

The main duty of electron devices is amplification and switching. Moreover, they can act as controlled resistors and capacitors. Their inherent nonlinear electrical characteristics are extremely useful in signal processing.

A study of the electrical behavior of the electron devices is required not only to design them to meet specific terminal electrical characteristics, but also to apply them efficiently in electronic circuits.

Electronic devices can be classified in electron tubes and solid-state devices. In spite of the revolutionary advance in solid state devices since the invention of the transistor by W. Shockley in 1948, electron tubes are still dominant in applications where large power at high frequencies is necessary. This is because of the different nature of current conduction in vacuum tubes and in the solid materials.

In this book, the operating principles underlying the operation of junction devices an field effect devices are clearly presented. To facilitate the understanding the electron emission phenomenon and the electrical properties of semiconductors are also introduced. After studying this book thoroughly, the student would be able to develop himself alone in this important branch of science and engineering. The reader needs only background in elementary physics, mathematics and circuit theory for easy understanding the material of this book.

The author is indebted to Dr. Nabil M. Saleh et al., 1987, Professor of Electronics, Communications and Computer Department, Faculty of Engineering, Ain Shams University, for the critical review and for his continued interest and encouragement throughout the writing of this book.

Abdelhalim Zekry
Professor of Electronics
Faculty of Engineering,
Ain Shams University.
1996

FORWARD

It is with pleasure that I could introduce this book on Electron Devices, a subject that will continue to be one of the most important subject of modern electronics. For a number of years, I have been acquainted with Dr. A. Zekry's outstanding teaching and academic research achievement. His expert knowledge of electronic devices is reflected in this book. I wish to congratulate him for this project.

Dr. Mohamed Nabil Saleh

professor of Electronics,
Dean, Faculty of Engineering
Ain Shams University, Cairo.

TABLE OF CONTENTS

Chapter 0 .... ***1***

0.1 Review Of Some Physical Principles 1

0.1 The classical model 1

0.2 Motion of an electron in vacuum under the influence of an electric field 2

0.3 Relativity theory 3

0.4 Second model of the Electron 4

0.4.1 Wave properties of the electron 4

0.4.2 Schroedinger Equation 5

Definition of the force in a potential field 6

Example: 6

Chapter 1 .... ***7***

Electron Sources And Electron Emission 7

1.1 Introduction 7

1.2 Electron States in an Atom - The Atomic Bohr Model 7

1.3 Solid Materials as Electron Sources 8

1.3.1 Energy Band Diagram of Crystals and the Workfunction 8

1.3.2 State Density Function N(W) 10

1.3.3 Energy Distribution Function $\rho(W)$ of Electrons in the Conduction Band 12

1.3.4 The Emission Current Density-Dushman Equation 14

1.3.5 Effect of an Additional Potential Barrier on the Thermionic Emission Current 17

1.3.6 Dependence of Thermionic Emission Current on Temperature and Work function of the Cathode Material 18

1.3.7 Properties of an Ideal Cathode Material 19

1.3.8 Practical Cathode Materials 21

(a) Tungsten cathodes 21

(b) Thoriated Tungsten Cathodes: 21

(c) - Oxide Coated Cathodes 22

1.3.9 Types of Cathode (Geometrical Construction) 23

1.4 Other Types of Electron Emission 24

1.4.1 Secondary Electron Emission 24

1.4.2 Photo-Emission 25

1.4.3 Field Emission 25

Chapter 2 .... ***26***

PHYSICS OF SEMICONDUCTORS 26

2.1 Introduction 26

2.2 Crystal Structure 27

2.2.1 Metallic Crystals 29

2.2.2 Semiconductor Crystal 29

2.2.3: Two Dimensional Representation of Si Crystal 31

2.3 Energy Band Diagram 32

2.4 Semiconductor Materials at Thermal Equilibrium 34
2.4.1 The hole concept 34
2.4.2 Thermal Generation Rate of Electron-Hole Pairs and the Mass Action Law: 35
2.4.3 Doped Semiconductors 40
2.4.3.1 n-type Semiconductors 40
2.4.3.2 p-type Semiconductor 44
2.5 Semiconductor at Non-equilibrium 48
2.5.1 Influence of an Electric Field on a homogeneous Semiconductor. Drift Current 48
2.5.2 Diffusion Current 53
2.5.3 Recombination and Mean lifetime of the Minority Carriers ... 56
2.6 Recombination mechanism 62
2.6.1 Statistics of the recombination processes 65
2.6.1.1 Two Particles Processes 65
2.6.1.2 Three Particle Processes 70
2.6.2 Dependence of the lifetime due to different recombination mechanisms on doping concentration. 73
2.6.3. Dependence of the Lifetime due to Different Recombination Mechanisms on Temperature 74
2.7 Basic Semiconductor equations 75
2.8 Transient Behavior of Disturbed Semiconductor Materials 77
CHAPTER 3 79
PN JUNCTION DIODE 79
3.1 Introduction 79
3.2 Some Production Methods of PN Junctions 79
3.2.1 EPITAXY: 80
3.2.2 Solid-State Diffusion 81
3.3.1 Impurity Distribution of Epitaxial PN Junction 82
3.3.2 Impurity Distribution of Diffused PN Junction 83
3.4 Qualitative Description of the Electrical Properties of a PN Junction at Thermal Equilibrium 83
3.5 The Built-in Voltage φ 87
3.6 The electrostatics of PN junctions 89
The Potential Distibution V(x) 92
Potential distribution in the p-side. 92
Potential distribution in the n-side: 93
Maximum electric field E_{max} 94
3.6.1 Order of Magnitude of Diffusion and Drift Currents at Thermal Eauilibrium in the transition Region: 95
3.7 Biased PN Junction, the Law of the Junction 95
3.8 Static I-V Characteristic of a PN Junction Diode 104
3.8.1 Qualitative Description of the Operation of an Ideal Diode .. 104
3.9 The Actual I-V Characteristics 114
3.9.1 Breakdown Mechanisms 115

3.9.2 Avalanche Breakdown Voltage 116
3.10 The PN Junction Diode as A circuit Element 118
3.10.1 The Static Resistance 118
3.10.2 Small Signal Parameters of a PN Junction Diode 119
3.10.2.1 Small Signal Resistance 119
3.10.2.2 PN Junction Capacitances 120
3.11.1 The basic diode circuit 124
Piecewise linearization of the diode I-V characteristics: 125
Example (1): 126
Example (2): 126
Example (3): 127
Geaphical solution: 129
3.12 Some diode applications: 130
i.. Half-wave rectifier: 130
ii.. The full-wave rectifier: 131
iii.. The full-wave bridge rectifier: 132
The diode clipping circuits: 132
(i) The positive clipping: 132
(ii) The negative clipper circuit: 133
The clamping circuit: 133
The voltage multiplication circuit: 134
The diode logic circuits: 135
Diode mixing circuit and frequency Conversion: 135
CHAPTER 4 137
THE BIPOLAR TRANSISTOR 137
4.1 Construction 137
4.2 Qualitative description of the transistor action 137
4.3 The Forward Active Operation 139
4.4 Definition of Some New Parameters 142
4.5 Minority Carrier Distribution in the Base and Approximate expressions for γ ,α_T and α 145
4.6 Shockley Theory 151
Exact Expressions for γ, α_T and α 151
4.7 The Ebers-Moll Model 154
4.8 Graphical Representation of I-V Characteristics of a pnp transistor 157
4.8.1 Static Characteristics of the Transistor in Common Base Circuit 160
4.8.2 I-V Characteristic of a Transistor in a Common Emitter Circuit 162
4.8.3 The Input Characteristic 164
4.9 Voltage Ratings of the Transistor 167
4.10 Transit Time 168
4.11 The transistor as a circuit element 170
Example: 173
Graphical Solutions 174

Combined piece wise linear model and graphical solution: 175
The universal biasing circuit of a transistor amplifier: 175
The transistor amplifier circuit: 176
(i) The graphical analysis: 178
(ii) The small signal equivalent circuit: 180
Chapter 5 ***186***
Field effect transistors (FET) 186
5.1 The junction field effect transistor 186
Introduction: 186
Construction of the JFET: 186
Device operation: 187
Characteristic points on I-V curves: 191
The I-V relationships: 191
Numerical example: 195
The breakdown voltage: 196
The P-JFET: 197
The MESFET: 197
5.2 The metal- oxide silicon field effect transistors (MOSFET): 197
The MOS capacitor: 198
The characteristics of the MOS-capacitor: 198
The threshold voltage V_{th} 201
The effect of the contact difference of potential Φ_{MS} and the interface charges on the relationship between V_G and the surface potential Ψ_S. 204
The contact difference of potential Φ_{MS}. 204
The MOS transistor 208
Construction: 208
The I-V characteristics: 209
The I-V relationship in the linear region: 211
The I-V relationship in the saturation region: 212
The effect of back gate bias V_{BS}: 213
The breakdown region: 213
The depletion n-MOS: 214
The enhancement p-MOST: 216
The enhancement junction MESFET: 216
FET as circuit element: 217
The dc operating point: 218
The graphical solution: 219
The analytical solution: 220
AC solution: 220
Small signal analytical solution: 221

Dar El Hakeem Press, Cairo
TEL : 2951038

ELECTRONIC DEVICES

A. ZEKRY

ELECTRONIC DEVICES

A. ZEKRY

Dar El Hakeem Press, Cairo
TEL : 2951038

ELECTRONIC DEVICES

A. ZEKRY

Chapter 0

0.1 Review Of Some Physical Principles

In analyzing the properties of electron devices, we often deal with electrons. Thus, it is important to describe the electron and to know some facts about its motion under the influence of an electric field. In classical physics, the electron is considered as a particle, while in modern physics, wave properties are observed. In this chapter, we shall briefly review the basic physical principles of electron motion. Our purpose is to determine the conditions for validity of each model; the particle and wave models.

0.1 The classical model

According to this model, the electron is a tiny negatively-charged particle. Its change q amounts to 1.6×10^{-19} coulomb and its mass at rest ***mo*** is 9.1×10^{-31} kg. Consequently, in order to determine the motion of the electron under the influence of different fields, the classical Newton's mechanics is used. If a force F acts upon a particle with mass m, it will be accelerated according to Newton's second law as follows,

$$\vec{F} = m\vec{a} \tag{0.1}$$

where $\vec{a}$ is the acceleration of the particle.

The above law applies if the mass does not change with the velocity of the particle, i.e. constant. Otherwise, we have to use the general form of the Newton's equation of motion,

$$\vec{F} = \frac{d}{dt}(m\vec{v}) \tag{0.2}$$

where the product of mass, m, and velocity, v, is the momentum of the particle.

When the velocity of the electron approaches the velocity of light in free space, the relativistic variation of the mass with respect to the particle velocity must be taken into consideration. According to Lorentz and Einstein, this relation is given by,

$$m = \frac{m_o}{\sqrt{1-\left(\frac{v}{c}\right)^2}} \tag{0.3}$$

where v is the velocity of the particle, c is the velocity of light $=3\times10^8$ m/s, and m_o is the mass at rest.

0.2 Motion of an electron in vacuum under the influence of an electric field E

One practical way to produce an electric field is to apply a battery on two metalic electrodes, which are situated in vacuum as shown in Fig.0.1. If an electron is present at the position x, it will move in the positive x-direction, in the opposite direction of the electric field. We are interested now to get a relation between the velocity of the electron at any position x, and the electric potential at the same point.

We shall consider the electron as a particle. Hence, we can write:

$$\vec{F} = m\frac{d\vec{v}}{dt}$$

Multiplying both sides by ***dx***, scalarily then one obtains:

$$\vec{F}.d\vec{x} = m\frac{d\vec{v}}{dt}.d\vec{x} \tag{0.4}$$

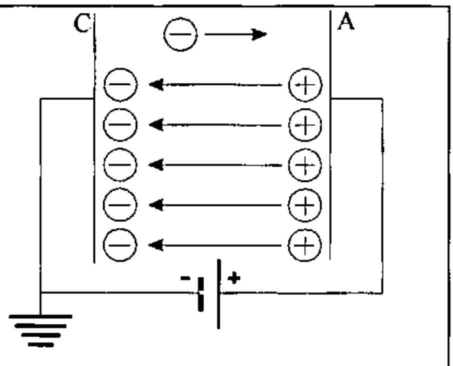

Fig.0.1: Electron in electric field

By definition, the force acting on the electron due to the electric field $\vec{E}$ is given by:

$$\vec{F} = -q\vec{E} \tag{0.5}$$

Substituting ***(0.5)*** in ***(0.4)***, we get:

$$q(-\vec{E}.d\vec{x}) = m\vec{v}.d\vec{v} \tag{0.6}$$

We know that the incremental potential difference $dV = -\vec{E}.d\vec{x}$, then from ***eqn.(0.6)***, we get: $q.dv = mvdv$

Integrating this equation from x=0 to any point x, we obtain:

$$q\int_{v(0)}^{v(x)} dV = \left(\frac{mv^2}{2}\right]_{v(0)=0}^{v(x)}$$

Therefore:

$$q[V(x)-V(0)] = \left[\frac{m}{2}v^2(x) - \frac{m}{2}v^2(0)\right] \qquad (0.7)$$

The kinetic energy, ***K.E.***, of a particle with mass ***m*** and velocity ***v*** equals $mv^2/2$, while the potential energy, ***P.E.*** = charge × potential.

The above equation then can be rewritten in the form:

$$P.E.\big|_{x=0} - P.E.\big|_{x} = K.E.\big|_{x} - K.E.\big|_{x=0} \qquad (0.8)$$

Equation *(0.7)* states that the decrease in potential energy of the electron is equal to the increase in its kinetic energy, which means that the electrostatic field is conservative.

Assuming that the potential of the plate C is equal to zero, and the electron starts at rest at $x=0$, then *eqn.(0.7)* reduces to the simple relation,

$$q.V(x) = \frac{mv^2(x)}{2}$$

$$V(x) = \sqrt{\frac{2e}{m}V(x)} \qquad (0.9)$$

This relation between the velocity of a charged patricle and its potential is of a great importance for determining the electrical characteristic of vacuum tubes as we shall see in chapter 3.

0.3 Relativity theory

We see easily from *eqn.(0.9)* that as the potential V is raised, the velocity of the particle ***v*** increases, and it can approach the velocity of light in free space. Here, the classical Newton's mechanics does not hold any longer. Instead, the relativistic mechanics founded by Einstein must by used. The relativity theory states that the energy equivalence of a mass ***m*** is equal to the product of this mass and the square of the velocity of light,

$$W = m\,C^2$$

Applying the above law on our problem, the energy equivalence W(0) of electron with a mass m_o at rest is given by the relation:

$$W(0) = m_o\,C^2 \qquad (0.10)$$

Now, if an electron falls down in the potential energy hill, Fig.(0.2), it acquires kinetic energy, its velocity will be increased. This means that the electron gains kinetic energy from the electric field. Its energy equivalence at any point x, greater than zero, will be higher than that at rest. Hence, the new energy equivalence of the electron at point x can be expressed by:

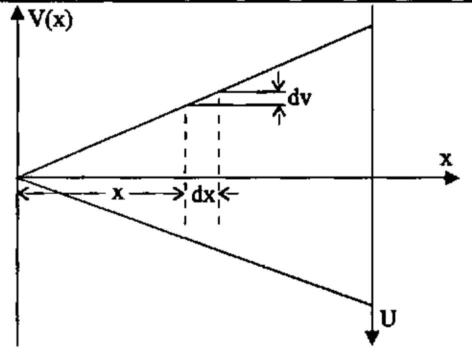

Fig.(0.2): Potential and potential energy distribution.

$$W(x) = m\,C^2 \qquad (0.11)$$

With m greater than m_o. Notice here that the velocity of light is time-invariant, i.e. it does not depend on time.

Since the electrostatic field is conservative, as previously proved in section 0.2, then the increase in the electron energy is equal to the mechanical work done by the electric field, we get finally the energy balance:

$$qV = mc^2 - m_o c^2 \qquad (0.12)$$

Combining *eqn. (0.12)* with Lorentz-Einstein *eqn. (0.3)*, we can get the actual velocity v of the particle.

0.4 Second model of the Electron

0.4.1 Wave properties of the electron

In many experiments in physics, it was found that the electrons show wave properties such as diffraction and interference. The motion of an electron in this case can be defined by applying the laws of the wave mechanics. The founders of wave mechanics are three young scientists, de Broglie, Heisenberg and Schroedinger. They won Nobel prize for physics for their contribution. De Broglie postulated that the wave length, λ, of a particle wave is inversely proportional to its mass ***m*** and velocity ***v***.

$$\lambda = \frac{h}{mv} = \frac{h}{p} \tag{0.13}$$

where ***h*** is Planck's constant = 6.625×10^{-36} J. sec., and ***P*** is the momentum of the particle.

This postulate is very important in wave mechanics. Specifically with the help of this equation, we can determine whether a moving particle behaves actually as a particle or as a wave. That is if λ is much smaller than the physical dimensions of the particle and the space in which the particle moves, then we shall measure only the particle properties, and we can use the classical mechanics to describe its motion.

On the other side, if λ is in the order of the physical dimensions of particle and the space in which the particle moves, such as the motion of an electron in an atom or in crystal, we have to use the wave mechanics to detect the physical behavior of the system.

0.4.2 Schroedinger Equation

Schroedinger equation represents the basis of the wave mechanics, as Newton's equation in the classical mechanics. The time independent Schroedinger equation can be written in the form:

$$\left(-\frac{\hbar^2}{2m}\nabla^2 + U\right)\Psi = W\Psi \tag{0.14}$$

with $\nabla^2 = \dfrac{\partial^2}{\partial x^2} + \dfrac{\partial^2}{\partial y^2} + \dfrac{\partial^2}{\partial z^2} \equiv$ Laplace operator, and

$$\hbar = \frac{h}{2\pi}$$

where *U(x,y,z)* is the potential energy, ***W*** is the total energy of the electron, ***m*** is its mass, and Ψ is the wave function to be determined in space by solving the above differential equation with appropriate boundary conditions. Ψ describes totally the motion of the electron in the potential field ***U***. The