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ISTANBUL AYDIN UNIVERSITY
INSTITUTE OF GRADUATE STUDIES

EXPLORING THE TRANSISTOR ON-STATE AND OFF-STATE IMPEDANCE BY USING MATLAB

MASTER'S THESIS

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Department of Electrical and Electronics Engineering
Electrical and Electronics Engineering Program

SEPTEMBER, 2023

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APPROVAL PAGE

DECLARATION

I hereby declare with respect that the study “Exploring The Transistor On-State And Off-State Impedance By Using MATLAB”, which I submitted as a Master thesis, is written without any assistance in violation of scientific ethics and traditions in all the processes from the Project phase to the conclusion of the thesis and that the works I have benefited are from those shown in the Bibliography. (.../.../20...)

Nouha BOUFARES

FOREWORD

I would like to dedicate this work to many people whom participate and help me in practically and morally way to accomplish this desertion work in favorable conditions and without their support this thesis might not have been done.

First of all, I want to start by thanking God for giving me all these blessings, abilities and needful potentials throughout my life.

Secondly, I am greatly thankful to my parents specially my mother, for being, throughout my life, my source of inspiration and encouragement. And also, for sacrificing your whole lives to actively supporting me in my determination to rich my targets.

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September, 2023 Nouha BOUFARES

EXPLORING THE TRANSISTOR ON-STATEAND OFF-STATE IMPEDANCE BY USING MATLAB

ABSTRACT

Impedance parameters, also known as Z-parameters or network parameters, are used to describe the behavior of linear electrical networks. They relate the voltage and current at the terminals of a network element or a network of interconnected elements.

The transistor element is widely used in electronic design applications. It is known that the transistor element has very important functions in electronic designs for industrial purposes.

The aim of this study is to obtain mathematical formulas relating on-state and off-state impedance with other transistor’s parameters in common emitter transistor circuits, then check the effectiveness of each parameter, which enable us to more control the transistor in the purpose of enhancing its performance so the hole network efficiently.

For this purpose, the obtained formulas were investigated using MATLAB software. Obtained findings and parameters affecting on-state and off-state impedance states or called affecting factors are presented with the help of graphics.

In the off-state, a transistor is typically in a non-conducting state, and the collector current is approximately zero. Therefore, in the off-state of a transistor, the open-circuit collector current is considered negligible, or effectively zero. Whereas, in the on state of a transistor, the emitter-base voltage typically depends on the specific operating conditions and the transistor biassing. The voltage between the emitter and base terminals can vary based on the applied input voltage, load conditions, and the transistor's characteristics.

Keywords: Transistor’s Parameters, On-State & Off-State Impedances, Affecting Factors.

MATLAB KULLANARAK TRANSİSTÖRÜN DURUMDA VE DURUM DIŞI EMPEDANSININ KEŞFEDİLMESİ

ÖZET

Z parametreleri veya ağ parametreleri olarak da bilinen empedans parametreleri, doğrusal elektrik ağlarının davranışını tanımlamak için kullanılır. Bir ağ elemanının veya birbirine bağlı elemanlardan oluşan bir ağın terminallerindeki voltajı ve akımı ilişkilendirirler.

Transistör elemanı elektronik tasarım uygulamalarında yaygın olarak kullanılmaktadır. Endüstriyel amaçlı elektronik tasarımlarda transistör elemanının çok önemli işlevlere sahip olduğu bilinmektedir.

Bu çalışmanın amacı, ortak emitörlü transistör devrelerinde, açık durum ve kapalı durum empedansını diğer transistör parametreleriyle ilişkilendiren matematiksel formüller elde etmek ve daha sonra her bir parametrenin etkinliğini kontrol ederek transistörü daha fazla kontrol etmemizi sağlamaktır. performansı sayesinde delik ağı verimli bir şekilde çalışır.

Bu amaçla elde edilen formüller MATLAB yazılımı kullanılarak araştırılmıştır. Açık durum ve durum dışı empedans durumlarını etkileyen veya etkileyen faktörler olarak adlandırılan elde edilen bulgular ve parametreler grafikler yardımıyla sunulmaktadır.

Kapalı durumda, bir transistör tipik olarak iletken olmayan bir durumdadır ve kolektör akımı sıfıra çok yakındır. Bu nedenle, bir transistörün kapalı durumunda, açık devre kolektör akımının ihmal edilebilir veya fiilen sıfır olduğu kabul edilir. Oysa bir transistörün açık durumunda, emitör-taban voltajı tipik olarak spesifik çalışma koşullarına ve transistörün öngerilimlenmesine bağlıdır. Verici ve taban terminalleri arasındaki voltaj, uygulanan giriş voltajına, yük koşullarına ve transistörün özelliklerine göre değişebilir.

Anahtar Kelimeler: Transistörün Parametreleri, Durumda ve Durum Dışı Empedanslar,

Etkileyen Faktörler.

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LIST OF ABBREVIATIONS

A : Anode

B : Base

BJT : Bipolar junction transistor

C : Collector

E : Emitter

FET : Field effect Transistors

K : Cathode

LED : Light Emitter Diodes

N_{eff}: No. of effective carriers

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I. BASIC CONCEPTS

A. Introduction

Semiconductors are materials which could be used as conductor or insulator depending to its ability to conduct the current which is called conductivity, which explains the name. There are varies semiconductors materials such as silicon, germanium, carbon etc. But still Silicon the most common material used to build semiconductor devices. Semiconductor devices proceed a range of useful properties: such as allowing current flow in one direction and preventing it in the other direction, showing variable resistance, and sensitivity to light or heat, and having a controlled conductivity depending to their uses. The electrical properties of a semiconductor material can be modified by adding a contourable number of impurities or by the application of electrical fields. That`s why, Semiconductors are the basic building block of modern electronics, including such as transistors, diodes and solar cells.

A diode is a double-side electronic piece that passes electric current in one direction (in this case, the resistance of an ideal diode is zero) and in the other direction shows a very high resistance (infinity) against the flow of current. This property of the diode caused it to be referred to as a valve in the early years of making this electronic device. Currently, the most common type of diode is made of crystal semiconductor material. The most important application of a diode is to pass current in one direction (forward direction) and prevent current from passing in the opposite direction (reverse direction). As a result, the diode can be viewed as a one-way electric valve. This property of diode is used to convert AC current to DC current. Electrically, a diode will pass current by applying voltage in the right direction (positive to the anode and negative to the cathode). The amount of voltage that causes the diode to start conducting electric current is called the threshold voltage or forward voltage drop, which is about 0.6(v) to 0.7(v) volts (for silicon diodes). But when you apply reverse voltage to the diode (positive to cathode and negative to anode) no current flows through the diode except a very small current known as leakage current which is around a few μA or even less. This amount of current can usually be ignored in most electronic circuits and does not affect the behavior of other circuit elements. The more regular the structure of the crystal material used in making the diode, the better the diode will be and the leakage current will be less. The amount of leakage current in diodes with new technology practically tends to zero. But the important thing is that all diodes have a threshold for the maximum reverse voltage, if the reverse voltage exceeds it, the diode breaks (the crystal melts) and passes the current in the reverse direction. This voltage is called diode break reverse threshold.

According to the transfer of energy in the interaction of rays with materials, each of them will have effects that are sometimes useful and constructive and, in some cases, cause damage to the structure of materials. Following these interactions, there are changes in the intrinsic properties of materials such as mechanical properties, conductivity, crystal structure, characteristics of atomic bonding, melting temperature, magnetic properties, load capacity, fluorescence properties, plastic properties, elasticity, maximum tensile strength and even material color. These changes occur in electronic components, mechanical transducers, superconductors, temperature sensors, alloys, polymers, organic materials and metals in the structures that make up the equipment that are exposed to radiation. In some cases, the effects will be transient and fleeting, and in some cases, depending on the type of interaction and the energy of the rays and the sensitivity of the materials, they will be permanent. Knowledge of each of the changes caused by radiation can lead to progress in the design of radiation systems and the appropriate selection of materials used in the constituent structures.

Among the systems in satellites and spacecraft are electronic systems, the existence of these complex environments has caused more attention to the effect of space radiation on the performance of electronic components such as diodes, transistors and other electronic devices. Space rays have destructive effects on electronic circuits, so that they can even cause a space mission to fail in the initial moments. In addition, these rays cause the efficiency of electronic circuits to decrease over time. The source of these rays are particles trapped in the earth's magnetic field, solar particles and cosmic particles (Leroy & Rancoita, 2007).

The effect of radiation on semiconductor components includes the effect of displacement damage, ionization damage, single event damage and nuclear reactions.

Among these, atomic displacement and ionization damage are more important. The effect of ionization is the release of electrons from their atoms. The production of defects caused by single-occurrence damage and cores does not seem very important in comparison with the production of defects resulting from displacement damage. Displacement damage occurs when atoms come out of their place in the network (Reed & et al., 1997). Displacement damage occurs in elastic and inelastic neutron scattering reactions, where neutrons give some of their energy to the nucleus of an atom. To move an atom from the stable network, energy is required as much as the energy of the atom depends on Ed. If the energy transferred to the atom is more than E_d, the atom will come out of its place in the crystal lattice. These displacements in the crystal lattice produce atoms between lattices and vacancies, which are called Frankel pairs (Standard, 1993). The result of all these interactions is the production of stable defect states that create energy levels in the forbidden band and change the number of effective carriers (N_{eff}) in the P and n regions, which results in a change in the reverse current. The change in the reverse current can cause destruction and the failure of electronic circuits. Therefore, in space applications, it is necessary to predict the amount of current change in advance. To express the effect of radiation on silicon, it is generally assumed that the damage, with the amount of energy (Fraser, 1986).

B. Applications of Semiconductors

Semiconductors materials are mainly used to create semiconductor components which are the base of all electronic products. Diodes are one of the most widely used semiconductor devices in electronics, which acts like a one-way valve as, it allows the current flow only in one direction. Conversely, conductors conduct the current in both directions. Semiconductors are used too for transistors creation, which are used both for fast switching and for current amplification. that is used for switching applications to turn the current on and off or as amplifier to simply amplify the electric currents.

- **Diode Applications**

The most important practical application of the diode is to convert AC current to DC current. In many adapters, the current reduced by the transformer is reduced by one diode (half-wave rectification), two diodes (in a transformer with a three-port in secondary part), full-wave rectification, or four diodes (in a transformer with a two-port in secondary part). Note that the one-way voltage after these diodes has a ripple frequency twice the alternating frequency (in full wave mode) and in order to fully straighten the voltage, a flat capacitor with a permissible voltage, high capacity (according to the amount of current consumed) must be used and install it after observing the polarity and after the diode bridge.

In AM receivers (such as radio in the SW and IM bands and analog TV signals), the diode plays the role of a detector, so that the intermediate signal enters a diode after amplification in the intermediate frequency amplification section, and the output is the final signal. In special cases, when there is only access to direct electric current to turn on electrical devices, a diode is used at the beginning of the electric current path to prevent the electrical device from burning due to the reverse connection of the positive and negative wires. If this diode is in series with the consumer in the positive direction of current, it is called a rectifier diode. But if it is placed parallel to the consumer and reversed, it is called a protective diode in reverse bias. A type of diode called Zener is used in making a type of regulator (voltage regulator). In the application of junction diodes, like other electronic equipment, there are limitations. knowing these limitations helps the designer in choosing a diode that can meet the requirements of his desired circuit. The main limitations of the diode are the maximum current, maximum voltage, maximum power that can be dissipated, and the speed of disconnection/connection.

Maximum diode current/voltage:

The maximum current that the diode can pass depends on the type and cross-section of the diode, and usually the manufacturer specifies the maximum direct current and the maximum reverse current of the diode. Also, the maximum direct and reverse voltage of the diode is given by the manufacturer. It should be noted that the values given are for the room for the body of the diode.

Maximum dissipated power of the diode:

Among the factors that can cause the failure of an electronic component, the temperature rises above a certain limit. In resistance components, as we know, the consumed power appears as heat, which must be properly exchanged with the surrounding environment. The more the heat exchange with the environment, the less the problems caused by the increase in temperature. Parts that have more external surface can do this heat exchange better. For this reason, resistors or diodes that have a larger nominal power are made in larger physical sizes. Also, the type of materials used in the construction of the piece has a significant effect on this matter.

In junction diodes, an excessive increase in temperature can change the properties of the crystal or cause mechanical changes in its structure due to the non-uniformity of the coefficient of thermal expansion. Also, the melting of the solder used in the connections may cause the failure of the diode. Silicon diodes can be used up to 200° Celsius. To increase the heat transfer capability, auxiliary factors such as heat sinks, liquid flow, and air currents can be used by fans. In any case, according to the situation and conditions of installation, each diode will have the maximum power that they display.

Diode switching speed

In switch circuits or logic circuits, we usually deal with switching diodes. In these cases, you should pay attention to the limitation of the switching and connecting speed of the diode and choose the appropriate diode according to the desired switching and connecting frequency. Usually, the diodes that start with the name uf are diodes with a high switching and connecting speed.

- **Transistor characteristics**

The first transistor was made by scientists of Bell Laboratory in 1984. With the expansion of using in various equipment such as microprocessors, microcontrollers, rail transit, wind power generation devices and aeronautics, identifying the factors affecting their operation has become particularly important (Busarello & et al., 2024; Qi & et al., 2020; Jiang & et al., 2016). The relationships between currents and voltages and their changes in the transistor as well as the amplification factor depend on factors such as temperature, frequency and non-linearity characteristics of the elements. Therefore, it is usually not possible to determine the values correctly through mathematical formulations. To obtain these relationships, curves are used for describing the relationships between currents and voltages (according to the arrangement of the transistor).

These curves are:

1. Input characteristic curve

2. Transition characteristic curve
3. Output characteristic curve

- Input characteristic curve

The input characteristic curve of the transistor expresses the value of the input current in terms of the input voltage. As the input circuit is similar to a diode, its characteristic curve is similar to the I-V characteristic curve of a normal diode. It should be noted that in the transistor, the input characteristic curve is drawn for a certain voltage V_{CE}. If the V_{CE} changes, the characteristic curve will also change slightly. Of course, these changes are very minor and can be ignored in most cases. The value of voltage V_{CE}, for which the input characteristic curve is drawn, is specified by the manufacturer.

- Transition characteristic curve

The transition characteristic curve shows the relationship between the input and output current of the transistor for fixed values of V_{CE}. Because the current amplification factor is equal to the output to input current ratio, therefore, the amplification factor can be obtained from this curve. Current amplification factor is denoted by β. The value of β depends on the physical characteristics and construction of the transistor.

- Output characteristic curve

The output characteristic curve shows the relationship between output current and voltage for a given input current. If the amplifier is a common emitter, the input current will be I_B, the output current will be I_C and the output voltage will be V_{CE}. The amount of output current is a function of two factors, I_B and V_{CE}. That is, as I_B increases and decreases, the output current of I_C also decreases or increases. This article is also fixed about V_{CE}, but the effect of V_{CE} changes on I_C is small and, in some cases, negligible. On the other hand, I_B current depends on V_{BE}. The output characteristic curve of the transistor includes 3 cut-off, active and saturation regions. In the cut-off region, the base current is zero and the transistor current has not yet reached the conduction threshold. In the active region, the transistor is conducting, and with large changes in V_{CE}, the collector current changes little and the base current is constant. In the saturation region, the transistor is conducting, but with a slight change in V_{CE} (fraction of a volt), very large changes in collector current are observed. In other words, BJTs can be operated in three different states (active, saturation and cut-off). BJTs have some merits like low turn-on loss, proper durability and low maintenance price which make them a good choice for using in analogue circuits (He, 2022). According to Webster effect, the main disadvantage of BJT is low switching speed (Matsumoto & et al., 1996). In forward mode, base and emitter is short circuit and collector put a forward voltage in accordance with emitter. In this regard, with applying 5V voltage on collector, positive conducting is appeared. Also, common emitter connection, has a low input impedance because the input is connected to a forward bias and has a high output impedance because it includes a reverse-biased connection.

C. Thesis Purpose

Our purpose is to develop a mathematical model which describe the relation between the parameters which affect the behavior of a semiconductor device such as diode and transistor and then simulate and observe the sensitivity of each parameter. All of the analysis and modelling steps are simulated by MATLAB software. Impedance parameters known to as Z-parameters are very useful to describe the behavior of any linear electrical network. As, they relate the voltage and current at the terminals of a network elements. Also, the input/output impedances depend of the applied configuration and related changes according to the operation state. That`s why, on-state and off-state impedances will be studied as they affect the performance and the stability of the circuit.

D. Thesis Innovations

- Designing a mathematical model to determine the impedance level of the transistor in on-state and off-state.
- Evaluation of the impact of different parameters on transistor impedances.
- Comparison of the sensitivity level of transistor impedance to ambient temperature variation.

II. ELECTRONIC DEVICES

The cornerstone of electronic elements is silicon-based semiconductor material. All electronic elements, from diode circuit elements to integrated circuits, are produced as electronic circuit elements by converting them into semiconductor structures such as PN, PNP, NPN, PNPN, NPNP with some doping methods. Mostly in the field of microelectronics, measurements of majority current carriers, minority current carriers, and interlayer impedance between these semiconductor layers are meaningful and important. In this thesis, off-state and on-state impedance calculations are discussed.

A. Introduction

Bounded electrons of atoms and molecules in a solid form active energy level along with a forbidden bond between them. In a solid, due to the high number of electrons, the energy levels are very close to each other and are arranged in a band with increasing energy. The capacity band includes electrons that are bound to only one solid nucleus. For example, in silicon, they are in covalent bonds. The conduction band contains free electrons that can help the material to conduct electricity. Between the conduction and capacitance bands, there is an energy region in which there is no virtual level. This region is called forbidden band (E_g).

The width of this region determines whether the material is an insulator, a semi-conductor, or a conductor. In a semiconductor, the bandgap is approximately 1 electron volt. For example, at room temperature, for silicon, E_g = 1.12 and for germanium, E_g = 0.67 (Sze, 2021). The bound electrons of atoms and molecules in a solid can move from the capacitance band to the conduction band by gaining energy and leave an empty space in the capacitance band, which is called a hole. Both electron and hole carriers can move in the semiconductor electric field. The electron and hole densities are denoted by n and p respectively. The product of n and p in a semiconductor at a certain temperature is a constant value that is obtained through Equation (2-1).

$$n_p = n_i^2 \qquad (2\text{-}1)$$

In this equation, ni is the intrinsic carrier concentration, that is, the carrier concentration in the pure semiconductor and for silicon is equal to $1..\cdot 45 \times 10^{10}$ cm^3 (Adler, 1964). Usually impurity atoms with 3-electron capacity (boron) or 5-electron capacity (phosphorus, arsenic) are inserted into the silicon crystal lattice, which causes a change in the electrical characteristics of the semiconductor. The concentration of donor impurities is denoted by ND and the concentration of acceptor impurities by N_A. The concentration of free carriers in a silicon crystal doped with donor atoms is equal to $n = N_D$.

In this crystal, the majority of carriers are electrons which is called n-type silicon. Similarly, a silicon crystal doped with silicon acceptor atoms It is called p-type and the concentration of free carriers of the majority (holes) is equal to $p = N_A$. At very high temperatures, the concentration of spontaneous carriers increases and all semiconductors become spontaneous in a wide range of temperature, n is almost equal to N_D. This area is called non-intrinsic thermal area. At low temperatures close to 0 Kelvin, n decreases to a value much less than N_D, and as temperature tends to 0, n also approaches zero, this region is called freezing region. At the other end of the temperature scale, with increasing T, n becomes greater than N_D and asymptotically approaches ni. At temperatures close to 0 Kelvin, the thermal energy of the system is not enough to excite the electrons to the conduction band. A slight increase in temperature causes the release of electrons that are loosely attached to the donor sites. With further increase in temperature, almost all the electrons that have a loose bond are released and n becomes close to N_D and enters the non-intrinsic side from the point of freezing. By progressing in the intrinsic thermal direction, more electrons are excited from the energy gap, but their number is less than N_D. Finally, the electrons excited from the gap are equal to the electrons taken from the donors, and then they increase them and then absorb (Naron, 1975).

The movement of each charged atom due to the electric field is called drift. Whenever a semiconductor is placed in an electric field, the holes are accelerated in the direction of the electric field and the electrons are accelerated against the direction of the electric field, and current flows in the semiconductor. Thrust current is the load that passes through the page perpendicular to the flow direction per unit of time and is calculated through Equation (2-2) (Standard, 1993). Current density is defined as Equation (2-3) (Burger & Donovan, 1967).

$$\boldsymbol{I_p = qpv_dA} \tag{2-2}$$

$$\boldsymbol{J_p = qpv_d} \tag{2-3}$$

$\boldsymbol{p}$: No. of holes

$\boldsymbol{q}$: Electric charge of the hole

$\boldsymbol{v_d}$: Avg. velocity of the holes

$\boldsymbol{A}$: Cross-sectional area of the semiconductor

The thrust speed is a linear function of the applied electric field, which is obtained according to Equation (2-4). where μ_p is the hole mobility capability, proportionality constant between v_d and E. By combining Equations (2-3) and (2-4), Equation (2-5) is obtained, which is also true for electrons (Equation (2-6)). Equations (2-5) and (2-6) show that the electron and hole current density is linearly related to the applied electric field.

$$\boldsymbol{v_d = \mu_p . E} \tag{2-4}$$

$$\boldsymbol{J_p = qp\mu_p . E} \tag{2-5}$$

$$\boldsymbol{J_n = qn\mu_n . E} \tag{2-6}$$

$\boldsymbol{\mu_p}$: Hole mobility capability

B. Diodes

1. Basic Characteristics

Diode is one of the two types of semi-conductor parts that are used in many electronic circuits. It directs the electric current in one direction and prevents the current from passing through the circuit in the opposite direction. These parts are made of different semiconductor materials such as silicon or germanium. They are formed from the connection of two P and N impurity regions. In order to better understand what a diode is, we need to know how P-N junctions work in semiconductors. These holes and free electrons are attracted to each other at the junction of Nand P regions. They form a specific area that has a completely neutral electric charge. This neutral part in P-N junctions is called the depletion region which is shown in Figure (1).

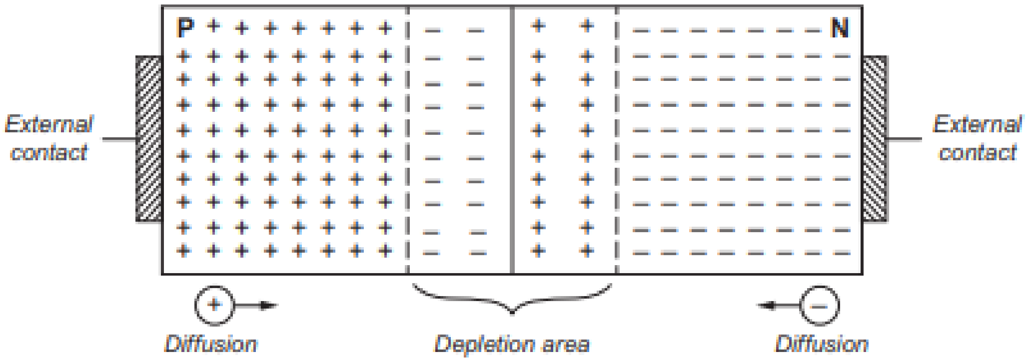

Figure 1. Simplified illustration of a junction diode structure (URL-1)

The presence of this area with a certain width is the main reason for the current passing through one side and not passing through the other side of the diode. To make the P region, gallium, aluminum and boron impurities can be added to the semiconductor material. Due to the addition of these materials, a large number of holes are created in this area. The P region in a diode is known as the anode and constitutes its positive polarity. For the N region, impurities such as phosphorus, antimony and arsenic are used. It will increase the number of electrons in this area. The N area is called the cathode and has a negative polarity. So, every type of diode, regardless of its specific features, has two bases called anode and cathode. The schematic of these two parts of each diode is shown in Figure (2) (URL-1). Its circuit symbol is a triangle pointing towards the cathode with a line perpendicular to its tip. This symbol indicates that the conventional current in the circuit is directed from the anode to the cathode. To understand the function of a real diode, we must know the physical processes that generate the characteristics of the diode terminals, and from which comes the nom of junction diode.

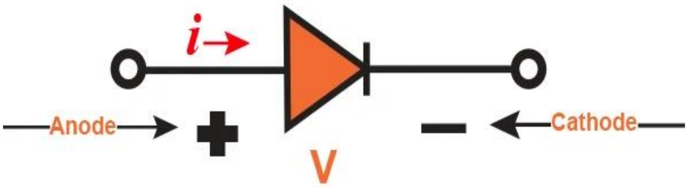

Figure 2. Symbol of Diode (URL-1)

Diodes are the simplest structure of semiconductors, which have many applications due to their performance in conducting electric current. Among their usual applications in satellites and spacecrafts, the following can be mentioned:

- Voltage modification, such as converting AC to DC
- Constant voltage source in electronic circuits
- Temperature measurement
- Protection against voltage deviations

The three main sources of ionizing radiation in space environments are:

1. Cosmic rays
2. Particles produced during solar particle events
3. Particles trapped in the magnetic belts of planets.

Most of the cosmic rays are composed of protons, but they include all elements and can have very high energies (up to 10^{11} GeV), which makes them very penetrating and leads to the inability to protect against them. The second category of radiations Ionizers in space originate from the sun. These particles include all natural elements from protons to uranium, and their flux depends on the solar period and can reach more than 10^{5} particles/cm2/s with an energy of more than 10 MeV/nucleon. Earth's magnetism (including intrinsic and external parts caused by the solar wind) is able to trap charged particles. Two distinct belts are formed by particles trapped in the Earth's magnetic field:

- Outer belt which consists mostly of electrons, and the
- Inner belt which consists mostly of proton (Hönniger, 2008).

As stated, protons play a significant role in the space radiation environment, and protecting the system against space protons requires investigating the effects of protons on electronic components. Radiation can affect electrical components in many ways. The beam can ionize the material of the part and cause an increase in current and charge (SEE), change the atomic structure of the material and cause a change in the performance of the part (TID), and if it has enough energy, it can cause physical and permanent damage to the part (DD). The presence of high levels of radiation hitting the silicon crystal of these structures in the radiation environment causes defects in them. The non-ionizing energy loss (NIEL) of the incident beam may cause silicon atoms to move from their place in the lattice and produce a sitting atom and a vacancy (Frenkel pair). The atom that has moved from its place in the lattice due to radiation is called primary knock-on atom (PKA). If the PKA energy is large enough, it causes the displacement of other silicon atoms from their position in the network and produces a cascade of defects. These defects cause the production of new energy levels in the forbidden band (Shoorian & et al., 2020; Srour & et al., 2003). One of the most important effects of radiation-induced defect centers on the electrical properties of silicon diodes is the thermal generation of electron-hole pairs near the middle band, increasing the leakage current, changing the discharge voltage, and reducing the lifetime of the carriers (Dale & et al., 1994).

The main motivation for serious study in the field of radiation damage caused by high-energy radiations on solid materials started from the sudden start of nuclear technology during World War II. Therefore, the starting point in the field of radiation damage is in 1943. Before that, many studies were conducted in the field of interactions of radiation with matter. In fact, since the discovery of X-rays and natural radioactivity, a lot of work had been done in the field of physics related to radiation and materials, which ultimately led to new theories in the field of atomic and crystal structures. Most of the initial studies in this field did not cause damage due to the presence of low energy and low intensity springs, but at the same time it was proved that radiation can affect the chemical structure of some materials. (Messenger & et al., 1997) compared Monte Carlo simulation results and analytical calculations of displacement damage caused by inelastic proton interactions in Si. By increasing the energy of the incident proton and reducing the sensitive volume, the range of the fissure fragments has reached the smallest dimensions and the variance of the damage from pixel to pixel has increased greatly. Monte Carlo method was used to describe the damage energy distribution. This simulation predicts the dark current histogram caused by 63 MeV protons more accurately than analytical methods. In (Summers & et al., 1993), the sensitivity of displacement damage and ionizing dose to the proton energy spectrum was calculated in order to obtain the minimum energy 100 eV for space protons. Obtain the differential energy of the proton to the minimum threshold energy for atomic displacement. Summers stated that in GaAs, Si and InP parts, there is a direct correlation between proton damage coefficients and NIEL. As a result, all that is needed for calculations is the proton differential flux, the measurements made for a proton energy and the NIEL value calculation (Jun & et al., 2003).

The work done in (Srour & et al, 1993) by considering the Coulomb scattering for protons with energy less than 10 MeV brought more accurate values for NIEL. In 2006, Srour with Palco have described the effects of displacement damage by emphasizing its most important mechanisms, i.e. increased carrier recombination and carrier production due to the levels created in the silicon energy gap due to radiation. In this work, the behavior of the NIEL transition regime from point defects (for NIEL values less than $5 \times 10^{-5}\,\mathrm{MeV}-\mathrm{cm}^{-2}/\mathrm{g}$) to subcluster defects (for NIEL values greater than $2 \times 10^{-4}\,\mathrm{MeV}-\mathrm{cm}^{-2}/\mathrm{g}$) has been modeled in terms of increasing the effect of subclusters with increasing NIEL.

Saturation occurs at relatively high values of NIEL where the number of produced subclusters increases linearly with NIEL. Practical conditions were achieved with relatively constant NIELs with penetration depth, single energy particles with high energy whose range in silicon is much larger than the dimensions of the irradiated part. In such conditions, NIEL can be considered equivalent to the displacement damage dose per unit of particle flux (Li & et al., 2018). Despite the greater accuracy of the experimental method, since practical experiments have a lot of cost and need a long time to execute, it is possible to save time by using simulation. Also, since the formation of point defects caused by collisions is almost impossible in experimental observations due to very short time and very small spatial scale (ps, nm), the modeling of defect formation and simulation of the part for understanding the complex mechanisms of defect formation and the function of the irradiated structures is necessary (Jafari, 2022; Razavi & Razavi, 2012).

2. The Static Characteristics of Diodes

In power Electronics applications, for each circuit we need to choose the right diode with the proper characteristics to ensure the best operation for our circuit. So, we have to consider the specifications of a diode. In order to understand the values existing on the datasheet of each diode which specify the diode, it is necessary to distinguish the two operational modes of a diode. In the equilibrium state of this piece, there are no electrons anywhere between the anode and cathode regions until forward bias voltage is applied to it and current flows through it (Figure (3)).

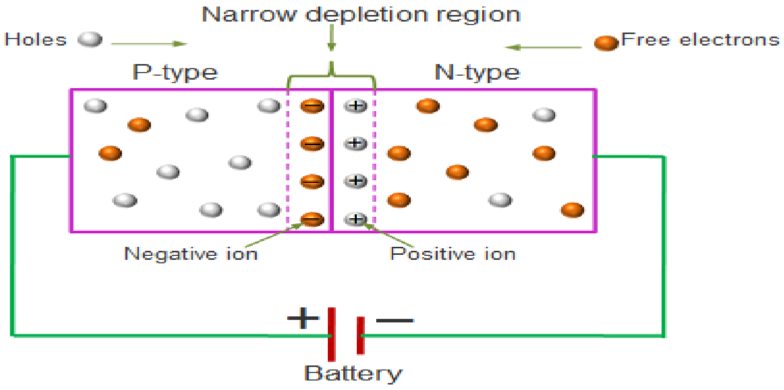

Figure 3. PN junction diode Forword-biased (URL-1)

Direct bias means a situation where the positive end of the diode (Anode) is connected to the positive end of the power source and its negative end (Cathode) is connected to the negative end of the power source. In this case, the width of the discharge area is much reduced and the electrons of the anode base easily move towards the cavities of the cathode base. If we reverse the direction of the supply applied to the diode and connecting the positive base of the power supply to the N region and its negative base to the P region causes that the holes retreat to the other side of the connection and the electrons move in the opposite direction. When this happens, very little current flows through the P-N junction and the width of the discharge region becomes much larger. As this area becomes wider, it becomes more difficult for the current to pass, and in fact, the diode does not allow the current to pass through itself. This is called reverse bias and is shown in Figure (4).

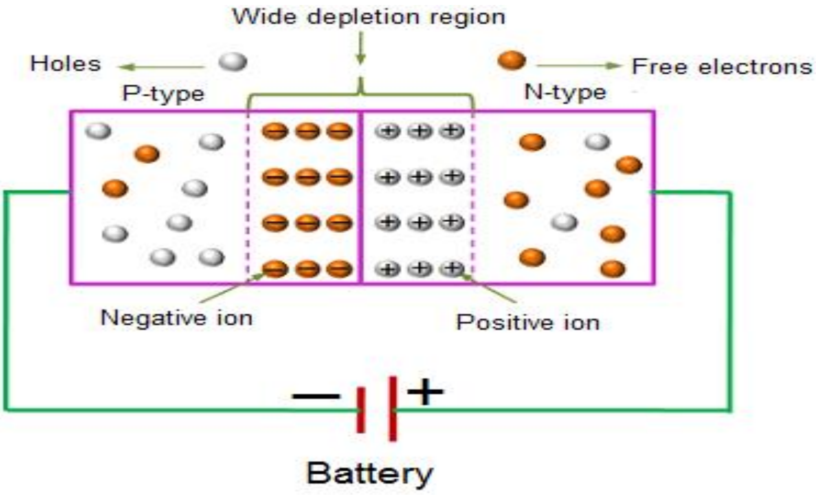

Figure 4. PN junction diode Reverse-biased (URL-1)

Using a diode in reverse bias may cause the breakdown of the discharge region and so-called breaking of the diode. Special diodes such as Zener or Avalanche can take over the direction of the reverse current and be used in this situation. In other words, in the case of direct bias, as the voltage increases, the amount of current passing through the diode increases almost linearly. But if the voltage is connected to it in the form of reverse bias, a small current will pass through it like open-circuit condition. These two conditions are shown in Figure (5).

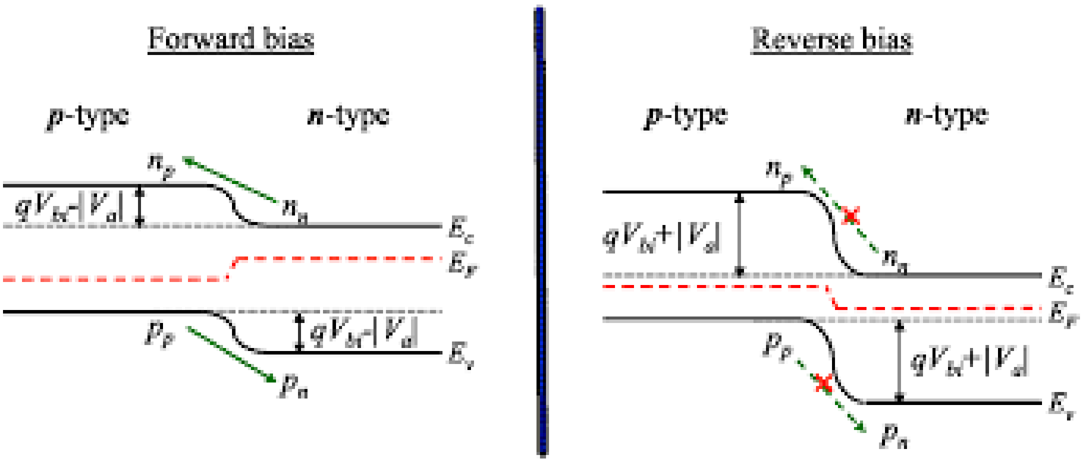

Figure 5. Energy Diagram of Forword and reverse biased diode (URL-1)

3. Characteristics of a Junction Diode

According to the structure of the semiconductors inside it, each diode has the ability to withstand reverse bias up to a certain voltage, which is called the break-reverse voltage (V_{BR}). After the reverse voltage exceeds this value, the structure of the diode is messed up and in this case the diode is burned and a strong current flow in the opposite direction in the circuit. As we can see in the Figure (6), in the first quadrant, the diode operates in forward bias mode, while in the second and third quadrant, the diode operates in reverse biased and break down regions respectively. This voltage (V_D) can reach 0.7 V for the silicon diode, as shown in the curve. During Reverse biased mode, the voltage through the diode is in negative potential so the current must be shown in negative direction. Diodes have many applications in electronics and electrical engineering, some of which are:

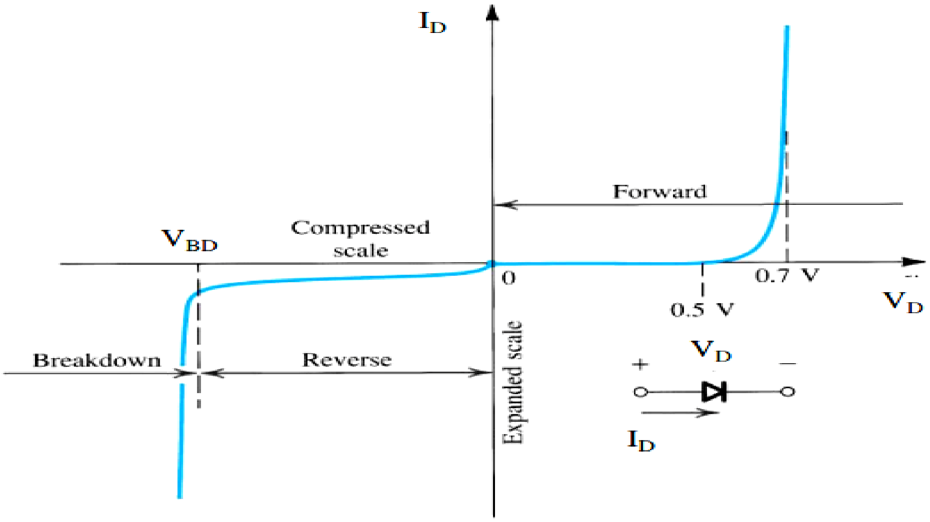

Figure 6. The i-v characteristic of a silicon junction diode (URL-1)

- **Rectifier:** Diodes are usually used to convert AC voltage to DC voltage in power supplies.
- **Voltage regulation:** Zener diodes and other types of voltage regulation diodes can be used to maintain a constant voltage in the circuit, even when the input voltage varies.
- **Signal detection:** diodes can be used to detect the signal in the circuit by rectifying and filtering it.
- **Cutting or limiting the signal:** Diodes can be used to cut off or limit the amplitude of the signal in order to prevent distortion or damage to the circuit.
- **Switching:** Since diodes allow current to pass through the circuit in only one direction, they can be used as a switch in electronic circuits.
- **Protection:** Diodes can be used to protect circuits from surge and reverse voltage.
- **Lighting:** Light emitting diodes (LEDs) are used in a wide range of lighting

applications.

- **Solar cells:** Photodiodes and other types of semiconductor diodes are used in solar cells to convert light energy into electrical energy.
- **Microwave applications:** Gunn diodes and other types of diodes are used in microwave applications such as amplifiers, oscillators and detectors.
- **Communications:** Laser diodes are used in optical communication systems such as fiber optic networks.

4. Schottky Diode

The solid phase reaction under the melting temperature between a thin metal film and a single crystal semiconductor can lead to the formation of a metal-semiconductor Schottky junction (Schottky junction or Schottky diode) in their interface. The main continuous motivation in the field of Schottky metal-semiconductor rectifier connections is the need for important features such as fast rectification and the ability to operate at high frequencies (Arashti & Sadeghzadeh, 2013). Such special properties make Schottky diodes suitable for high gain rectifiers, radio frequency applications, RF detectors and use in solar cells (Hudait & Krupanidhi, 2000).

Metal-semiconductor junctions are often used in integrated circuits, as MOSFET in detectors and solar cells. In addition, metal-semiconductor connections are rectifiers that are used in fast switching circuits, switching power supplies, microwaves, as well as complex semiconductor components and have been widely studied (Arashti & Sadeghzadeh, 2013). Therefore, understanding their structural and electronic characteristics has always been the focus of physics and electronics researchers. The properties of the interface, transport mechanisms and some structural parameters of the metal-semiconductor Schottky junction have been the subject of theoretical and experimental research in the past decades, but little experimental information is available on the formation of the Schottky barrier and the density of intermediate states (between the metal and the semiconductor) (Hudait & Krupanidhi, 2000). Also, the presence of a thin insulating layer between metal and semiconductor is an important factor that affects the behavior of Schottky diode (Guo & et al., 2016). Reliability and optimal quality of a metal-semiconductor connection is necessary for the optimal performance of the corresponding devices in electronic circuits (Chawanda & et al., 2010). For example, integrated circuit technology and internal connections require metal-semiconductor connections that have low thermal stability and resistance. Thermal annealing of the Schottky diode (after the manufacturing process) is the most common process used to create the desired quality and stability of these diodes (Doğan & et al., 2008; Yüksel, 2009).

In this project, the electrical characteristics of the Schottky diode (ideal factor, reverse saturation current and Schottky barrier height) fitting the experimental current-voltage (I-V) graphs based on the theory of thermion emission have been studied. In the following, the current-voltage characteristic of Al/p-Si Schottky diode was measured at different temperatures (temperature range of 15-300 kelvin degree) and by analyzing the results, the effect of the temperature on the electrical characteristics of the diode was determined.

C. Transistors

1. Basic Parameters

The primary use of a bipolar junction transistors (BJT) is current amplification, but BJTs can be used as amplifiers or switches in electronic equipment such as cell phones, industrial control systems, televisions, and radio transmitters. BJTs can be used as amplifiers, filters, rectifiers, oscillators, or even switches. If the transistor is biased in the linear region, the transistor acts as a linear amplifier or circuit. In order to be able to use the transistor as a switch or amplifier, the transistor must be fed with DC voltage. The operation of supplying voltage to the transistor ports is called biasing. According to transistor bases and diode equivalent circuit, there are 3 different modes for transistor biasing:

I. The base-emitter connection is in direct bias and the base-collector connection is also in direct bias. In this form, in this biasing mode, the two currents I_E (the current that passes through the emitter) and I_C (the current that passes through the collector) each take a separate path in the two-ring and only join together at the base. They are divided again. In this case, we say that the transistor is in switching mode.

II. The base-emitter connection is in reverse bias and the base-collector connection is also in reverse bias. In this configuration, both diodes are in reverse bias and in off-state. Therefore, the current I_E and I_C are close to zero (of course, a very weak current passes through the circuit due to the breaking of bonds at normal temperature). In this case, the transistor does not perform any action and is in the opposite bias and is so-called cut-off.

III. The base-emitter connection in direct bias and base-collector connection in reverse bias. So, there is a current in the base-emitter circuit.

The current passing through the collector is denoted by I_C, the current passing through the base is denoted by I_B, and the current passing through the emitter is denoted by I_E. In this condition, the current passing through the emitter is divided into two branches. Most of it passes through the collector. Therefore, the emitter current is equal to the sum of the base current and the collector current. In the conventional direction, the current leaves the positive pole of the battery and after passing through the external circuit, enters its negative pole. In this condition, the conventional direction corresponds to the base-emitter diode direction. The voltage that is placed between the bases and the emitter is V_{BE}, the voltage that is placed in the collector-base part is V_{CB} and the voltage that is connected between the collector-emitter is V_{CE}. In the other side, the voltage that supplies the collector is called V_{CC} and the voltage that injected the energy to the base are denoted by V_{BB}. Transistor arrangements in the circuit are formed in three types:

- Common-emitter (CE)
- Common-base (CB)
- Common collector (CC)

In the transistor, the input signal is always given to two of the three bases of the transistor, and the output signal is taken from its two bases, so that one of the bases is shared between the input and the output, so the name of the arrangement is chosen according to the common base.

2. Common-Emitter BJT Transistors

If two individual signal diodes are connected back-to-back, this will produce two PN-junctions connected in series and share a common P or N terminal. The combination of these two diodes produces a two junction with three terminals devices which represent the basic Bipolar junction transistor (BJT) (Figure (7)). So, we can define a Bipolar Junction Transistor as a component consists of two PN-junctions producing three connecting terminals namely emitter, collector and base.

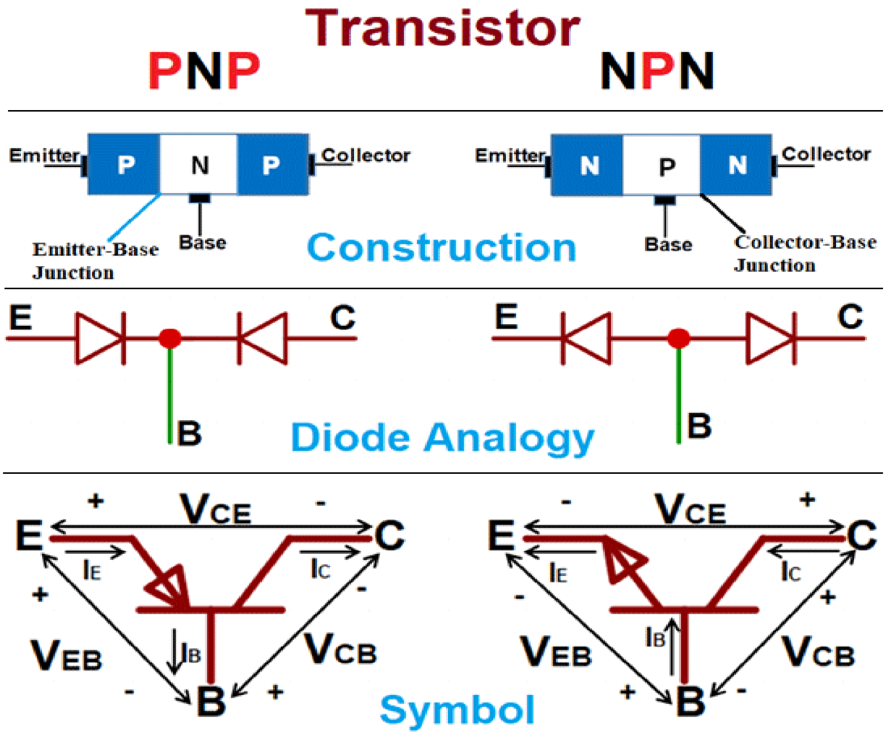

Figure 7. Symbol and Construction of Bipolar Junction Transistor BJT

In common-emitter (CE) configuration, V_{BE} and I_B are the input parameters and V_{CE} and I_C represent the output parameters (Zankawi, 2015), As shown in Figure (7). For CE configuration which is the most commonly used circuit in the applications of transistor-based amplifiers, the emitter current (I_E) is given by the Equation (2-7). Also, the current gain (α) is the ratio between I_C and I_E (Equation (2-8)) and its value is always less than unity. Another current gain (β) is defined as the ratio between I_C and I_B, which will be a quite larger (Equation (2-9)). According to these equations, if any small change occurs in the I_B, then I_C will change in a much larger way, so CE is controlled by the small changes of the current flowing in the base. This configuration is operating as inverter amplifier because the output voltage is 180° out-of-phase with the input voltage.

$$\mathbf{I_E = I_C + I_B} \tag{2-7}$$

$$\boldsymbol{\alpha} = {}^{\mathbf{I_C}}/_{\mathbf{I_E}} \tag{2-8}$$

$$\boldsymbol{\beta} = {}^{\mathbf{I_C}}/_{\mathbf{I_B}} \tag{2-9}$$

$\mathbf{I_E}$: Emitter current

$\mathbf{I_C}$: Collector current

$\mathbf{I_B}$: Base current

, $\boldsymbol{\beta}$: Current gains

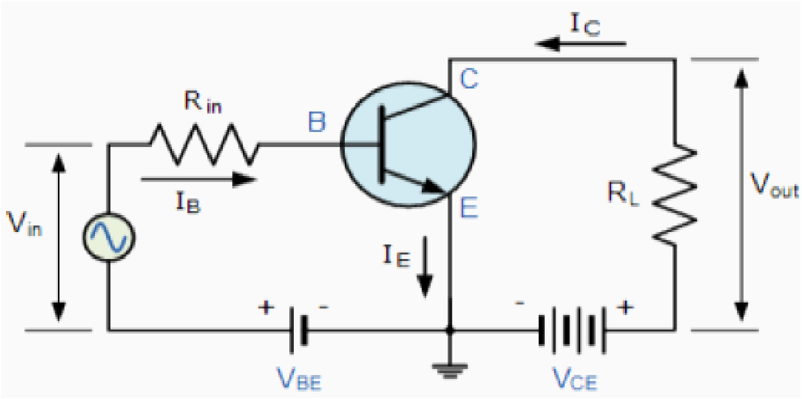

Figure 8. Schematic of common-emitter mode of BJT transistor (Uchida & et al., 2003)

A Bipolar transistor can be used for switching operations with two different states (cut-off and saturation). In other words, if it works in the saturation state, it will act like a closed switch “on-state” and when is operates in the cut-off state, it behaves like an open switch “off-state”. Both PNP and NPN transistors can be used as switches. In this project, an NPN Transistor in CE mode will be used for studies. In this status, I_E and I_C currents are determined with Equations (2-10) and (2-11), respectively. The measurements made for the common-emitter mode are explained step by step below.

$$I_E = -\frac{I_{E0}}{1-\alpha_N\alpha_I}\left(e^{qV_{EB}/kT}-1\right) + \alpha_N\frac{I_{C0}}{1-\alpha_N\alpha_I}\left(e^{qV_{CB}/kT}-1\right) \tag{2-10}$$

$$I_C = \alpha_N\frac{I_{E0}}{1-\alpha_N\alpha_I}\left(e^{qV_{EB}/kT}-1\right) - \frac{I_{C0}}{1-\alpha_N\alpha_I}\left(e^{qV_{CB}/kT}-1\right) \tag{2-11}$$

$\mathbf{I_{E0}}$: Emitter current

$\mathbf{I_{C0}}$: Collector current

$\boldsymbol{\alpha_N}$: Base current

$\boldsymbol{\alpha_I}$: Current gains

q : Charge of electron

$\mathbf{V_{EB}}$: Emitter-base voltage

k : Boltzman’s constant

T : Temperature

The Diagram of circuit connections of emitter – base - collector of this transistor is shown in Figure (9).

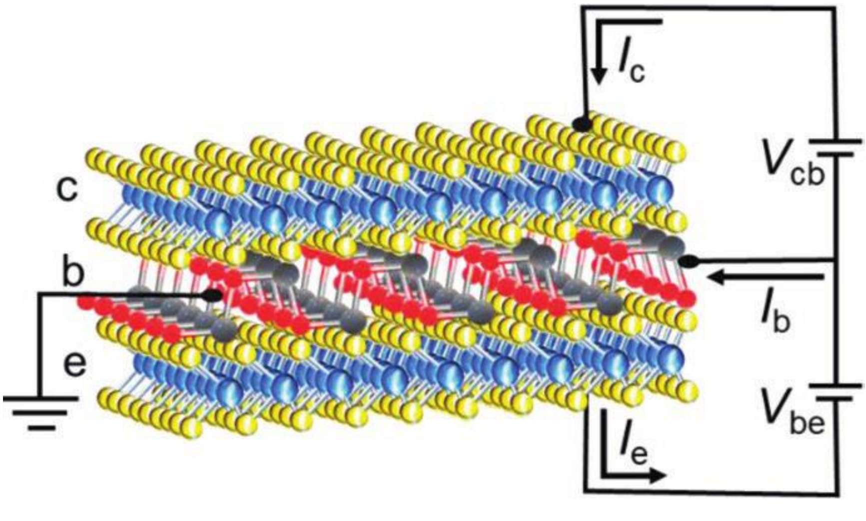

Figure 9. Schematic of CE circuit connections of BJT transistor (Lin & et al, 2017)

In this transistor, the voltage source V_{BE} is connected to the base and the voltage source V_{CE} is connected to the collector base. In operating conditions, usually the voltage V_{BE} is kept constant and the changes of I_C according to V_{CE} are measured. This is shown in Figure (10).

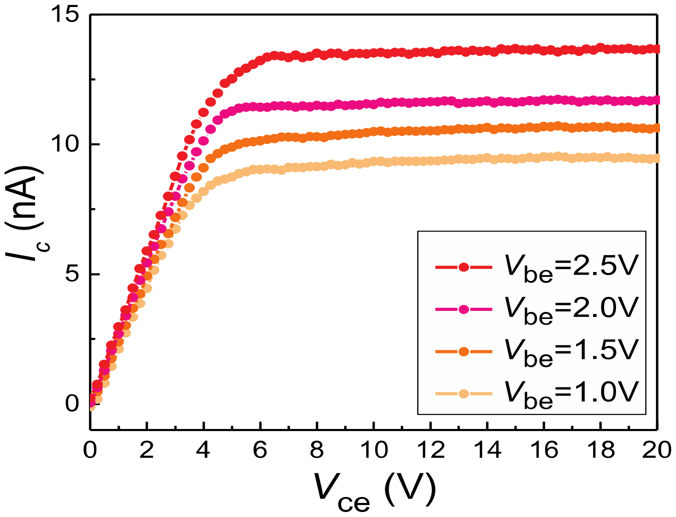

Figure 10. Variation of I_c vs. V_{CE} at different V_{BE} values (Lin & et al, 2017)

If the value of V_{BE} exceeds the specified threshold value, then the break-down is occurs. To avoid such an event, the voltage is kept in a range lower than this, which is considered V_{BE} = 2.5v in this section. In this regard, as the voltage V_{CE} increases, the I_C current increases until it reaches saturation. In the saturation state, the value remains constant and does not change. This condition is achieved when $V_{CE} > 4$ and it is called the active region. In these operating conditions, the base connection plays an important role in amplifying. In normal mode, the I_C current is a function of V_{CE} and its sensitivity to the corresponding voltage is shown in Figure (11). In the common emitter transistor, the ratio of the collector current (I_c) to the base current (I_b) is introduced as the current gain (β), which is actually a function of V_{CE} (Figure (12)).

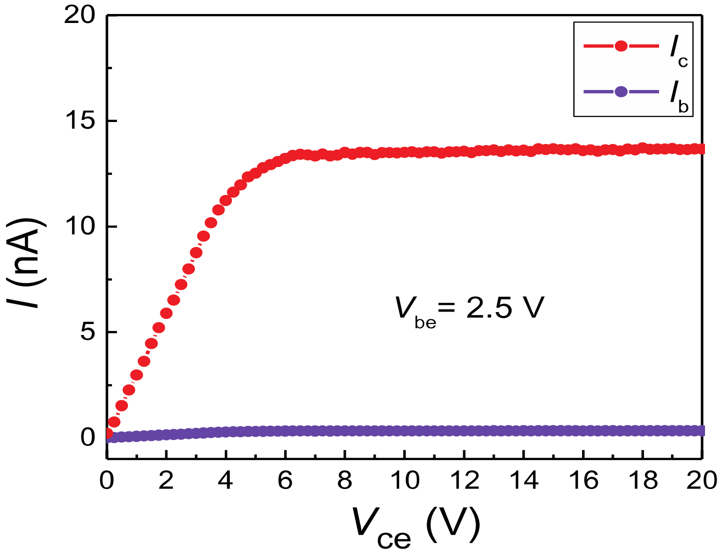

Figure 11. Variation of I_b and I_c vs. V_{ce} (V_{be} = fixed) (Lin & et al, 2017)

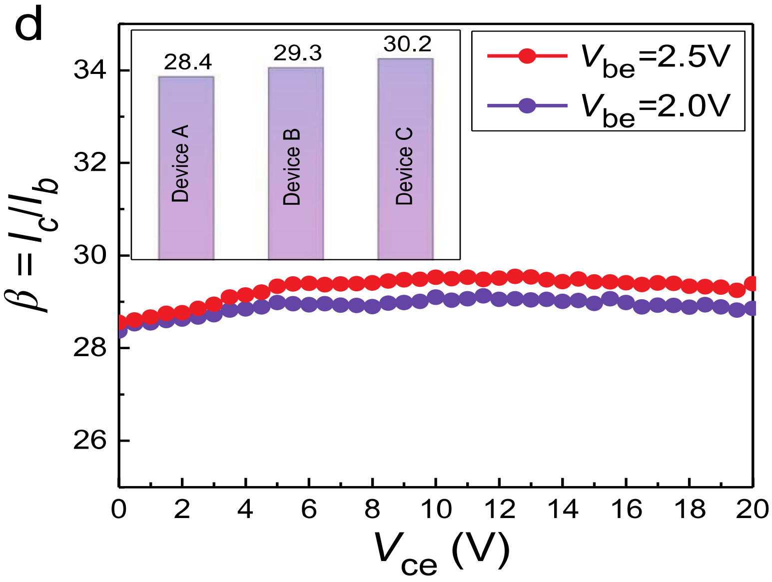

Figure 12. Variation of β vs. V_{ce} (V_{be} = fixed) (Lin & et al, 2017)

III. RESEARCH METHODOLOGY

A. Introduction

In this thesis, a mathematical model has been developed to control the different parameters which related the input and output of a semiconductor devices integrated in different circuits. The obtained formulas will be investigated using the MATLAB program All the findings regarding the parameters which affect the on state and off state impedance are presented with the help of graphs. The graphs will be discussed in a way to check the impact of all the parameters and then obtain the results regarding our studies.

The input/output impedances of a transistor depend of its applied configuration and related changes according to the operation state. In the other side, on-state and off-state impedances of a transistor affect the performance and the stability of the circuit. Therefore, these impedances should be taken into account when designing circuits consist of transistors.

The leakage current in a reverse biased diode has two components. One component is the inherent current of the diode and the other is the volume component which depends on the concentration of production centers (Sze, 2021). It has been observed experimentally that the leakage current in a reverse bias diode increases linearly with the current. The dependence of the current on the flow of ion particles can also be calculated as Equation (3-1). In this model, α is the slope of the flow. Figure (13) shows the increase in current due to the increase in flux. The proportionality of the flow with the flow results that the increase of the flow is due to the linear creation of the centers of active production and composition, which dominates the spontaneous reverse flow.

$$\Delta I = I(\varphi) - I(0) = \alpha \cdot \varphi \tag{3-1}$$

$\boldsymbol{\alpha}$: Reverse current damage constant

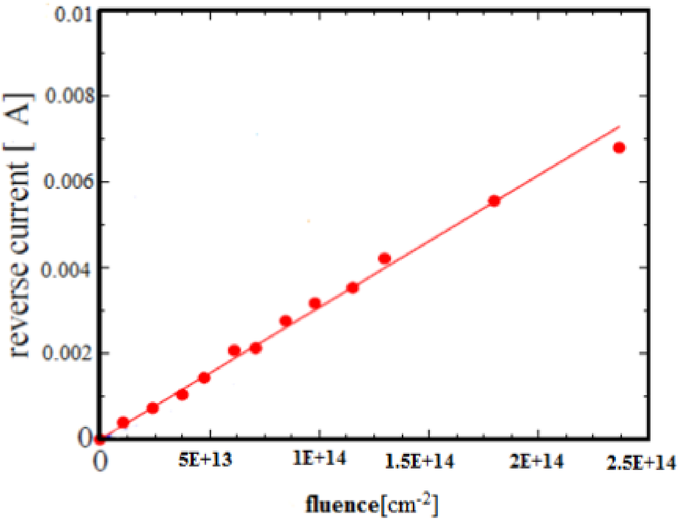

Figure 13. Leakage current in a reverse bias diode Vs. main current (Sze, 2021).

The relationship between the leakage current and ionizing radiation flux is based on the assumption that the current produced by the body is proportional to the density of induced radiation defects and controls the measured current. A reverse-biased p ± n junction is shown in Figure (14). When ion particles pass through this junction, electron-hole pairs (e-h) are generated along the path of the particles. These pairs are already unable to recombine and they move towards the anode (electrons) or cathode (holes) by the electric field in the discharge side and are separated.

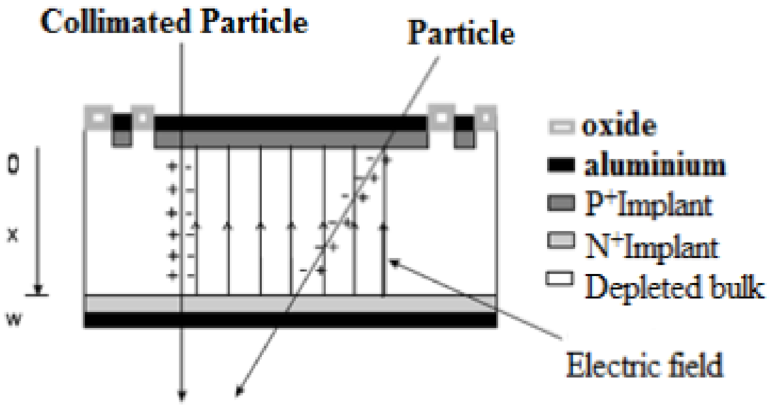

Figure 14. Carriers generation along the path of particle (Grill & et al., 1992)

The movement of the generated charge creates a signal on the diode electrodes according to Ramo's law, which is shown in Equation (3-2) (Grill & et al., 1992). The induced current is obtained by Equation (3-3). As can be seen, the current has a direct relationship with the electric field. In a fixed flux value, the stronger the reverse voltage and the electric field, the higher the charge collection efficiency due to radiation and the higher the current.

$$\Delta Q = Q.\cdot \frac{\Delta x}{w} \tag{3-2}$$

$$i(x) = \frac{dQ}{dt} = \frac{Q}{w}.\cdot \frac{dx}{dt} = \frac{Q}{w}.\cdot \mu E(x) \tag{3-3}$$

$\boldsymbol{w}$: Thickness of the bond

In fact, a weak electric field is not able to collect all the generated charges, and the stronger the field, the more charges it can collect and the current increases. This increase in current causes a constant increase in the damage of reverse current α. Leakage current is strongly influenced by temperature. The temperature dependence of the leakage current for diodes has been widely studied and the obtained data is calculated by Equation (3-4) (Barberis & et al., 1993; Chilingarov & et al., 1995; Lemeilleur & et al., 1995; Hall, 1991). The value of E_A has been obtained by different experiments from 0.6 to 0.7 (Adler, 1964; Naron, 1975). The reverse current damage constant α also changes with temperature. Because with the increase in temperature, the size of the energy gap of semiconductor materials decreases, and as a result, in a constant amount of flux, more carriers are produced and α increases. The size of the energy gap for silicon in terms of temperature is given in Equation (3-5) (Burger & Donovan, 1967). At high temperatures, the constant increase of reverse current damage α is very slow and insignificant. The reason for this problem is that at high temperatures, the number of inherent semiconductor carriers is greatly increased and the carriers caused by radiation can be ignored. In this case, they say that the semiconductor is intrinsic.

$$I \propto T^2 exp\left(-\frac{E_A}{k_B(T + 273.\cdot 2)}\right) \tag{3-4}$$

$$E_g = 1.1557 - \frac{7.021 \times 10^{-4} T^2}{1108 + T} \tag{3-5}$$

$\boldsymbol{E_A}$: Activation energy

$\boldsymbol{T}$: Temperature in Celsius

B. Diode Studies

The value of the flowing current (I) for the Schottky diode in forward bias at the voltage more than 0.2 V, can be obtained using the Equation (3-6) (Adler, 1964). The reverse saturation current calculated by Equation (3-7) (Figure (15)).

$$\mathrm{I} = \mathrm{I}_0 . \exp\left(\frac{\mathrm{eV}}{\mathrm{nkT}}\right) \tag{3-6}$$

$$\mathrm{I}_0 = AA^{*}T^{2}\exp(\frac{-e\varphi_{\mathrm{B0}}}{\mathrm{kT}}) \tag{3-7}$$

I_0 : Reverse saturation current

e : Charge of electron

k : Boltzmann's constant

T : Temperature

V : Applied voltage

n : Design factor

A^{*} : Richardson's constant

φ_{B0} : Schottky resistance height

A : Cross section of diode

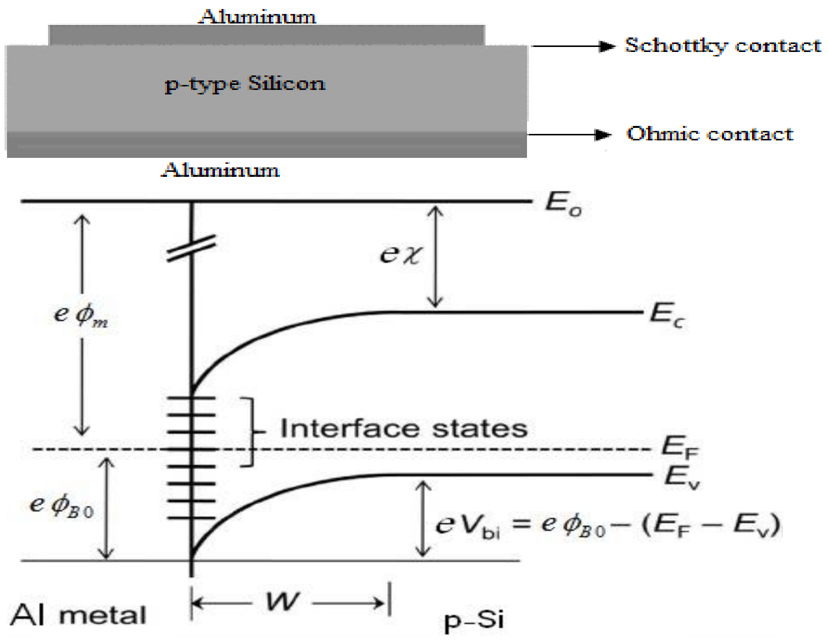

Figure 15. Schematic of Schattky diode (Adler, 1964).

C. Transistor On-State and Off-State Impedance

As we mention before, as the Transistor is a three terminal device made from different semiconductor materials, it is a multi-functional device. It could be used as either a conductor or an insulator. It`s ability to move between these two states makes it have two basic functions: "amplification" (analogue electronics) and "switching" (digital electronics). So, a bipolar transistor can be operated within different regions. The input/output impedances of a transistor depend of its applied configuration and related changes according to the operation state. In this thesis, an NPN Transistor will be considered as a switch in a common-emitter configuration. It is clear that when the applied voltage is not enough at the input, the transistor operates in cut-off mode and acts as an open circuit. Otherwise, When the input voltage reaches certain level, the transistor will allow passing the current in this case it will act as close switch.

1. On-State Impedance

In this situation, the transistor is operating in the saturation mode (V_{CE} < 0.7(v)) and I_B is increased until I_C is independent of it (Figure (16)). and consist of the following characteristics:

- The input and base are connected to V_{CC}.

- The V_{BE} is greater than the cut-in voltage (normally 0.7 V).
- Both the BC and BE junctions are forward biased.
- The transistor operates as a closed switch (on-state).
- The maximum amount of I_C can be achieved by maximizing the I_B current.

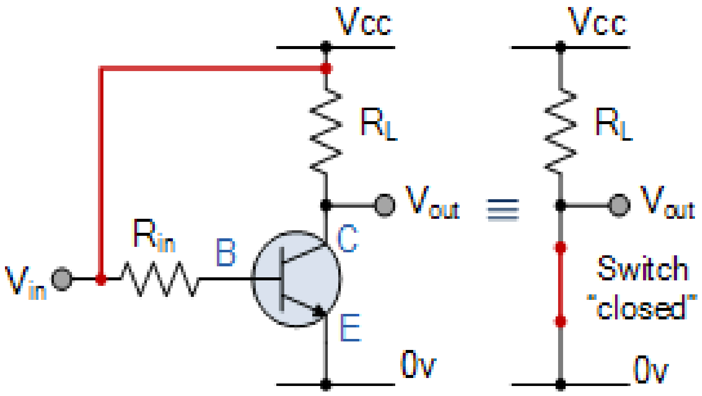

Figure 16. NPN Transistor in saturation mode (Leroy & Rancoita, 2007)

In this regard, since both junctions are forward biased, I_C is determined by equation (3-8). Then, with some manipulations like as equation (3-9), V_{CB} can be calculated as equation (3-10). Finally, the on-state impedance can be defined as equation (3-11).

$$I_C = \alpha_N \left(\alpha_I \frac{I_{C0}}{1 - \alpha_N \alpha_I} \, e^{qV_{CB}/kT} - I_E \right) - \frac{I_{C0}}{1 - \alpha_N \alpha_I} \, e^{qV_{CB}/kT} \tag{3-8}$$

$$\begin{aligned} I_C + \alpha_N I_E &= e^{qV_{CB}/kT} \left(\alpha_N \alpha_I \frac{I_{c0}}{1 - \alpha_N \alpha_I} - \frac{I_{c0}}{1 - \alpha_N \alpha_I} \right) \\ &= e^{qV_{CB}/kT} \left[- I_{C0} \left(\frac{1 - \alpha_N \alpha_I}{1 - \alpha_N \alpha_I} \right) \right] = -I_{C0} \, e^{qV_{CB}/kT} \end{aligned} \tag{3-9}$$

$$\frac{qV_{CB}}{kT} = \ln\left[- \frac{I_C + \alpha_N I_E}{I_{C0}}\right] \tag{3-10}$$

$$Z\_On = \frac{V_c}{I_c} = \frac{kT}{qI_C} \ln\left[\frac{I_{C0}}{I_C + \alpha_N I_E}\right] \tag{3-11}$$

2. Off-State Impedance

In this state, the transistor operates in the Cut-Off mode (off-state) and the following characteristics will be verified (Figure (17)):

- The input I_B is grounded ($I_B = 0$).
- The V_{BE} is less than the cut-in voltage (e.g. $V_{BE} < 0.7$ V).
- Both BC and BE junctions are reverse biased.
- The transistor acts like open switch (off-state)
- The V_{CE} is in the maximum condition, $V_{out} = V_{CC}$ and $I_C = 0$.

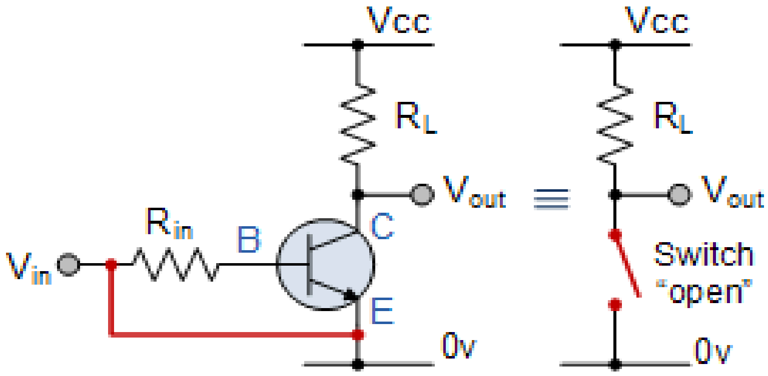

Figure 17. NPN Transistor in cut-off mode (Leroy & Rancoita, 2007)

In this case, since $V_{EB} << \frac{KT}{q}$ and $V_{CB} << \frac{KT}{q}$, the I_C and I_E are calculated as Equations (3-12) and (3-13), respectively. Then, V_{EB} and V_{CB} are defined as Equations (3-14) and (3-15), respectively. Finally, the off-state impedance is calculated as Equation (3-16).

$$I_C = -\alpha_N \frac{I_{E0}}{1-\alpha_N\alpha_I} + \frac{I_{C0}}{1-\alpha_N\alpha_I} = \frac{I_{C0}-\alpha_N I_{E0}}{1-\alpha_N\alpha_I} \tag{3-12}$$

$$I_E = -\frac{I_{E0}}{1-\alpha_N\alpha_I}\, e^{qV_{EB}/kT} - \alpha_I\left(I_C - \alpha_N \frac{I_{E0}}{1-\alpha_N\alpha_I}\, e^{qV_{EB}/kT}\right) \tag{3-13}$$

$$V_{EB} = \frac{kT}{q}\ln\left(-\frac{I_E + \alpha_I I_C}{I_{E0}}\right) \tag{3-14}$$

$$V_{CB} = \frac{kT}{q}\ln\left(-\frac{I_C + \alpha_N I_E}{I_{C0}}\right) \tag{3-15}$$

$$\mathrm{Z\_Off} = \frac{V_c}{I_c} = \frac{V_c(1-\alpha_N\alpha_I)}{I_{C0}-\alpha_N I_{E0}} \tag{3-16}$$

D. Ionization Effect on BJT Transistor

Through ionization, hole flow can be improved. For a better description of this phenomenon, the energy band diagram is shown in Figure (18). This diagram can explain the hole absorption process between Conduction band and Window junction.

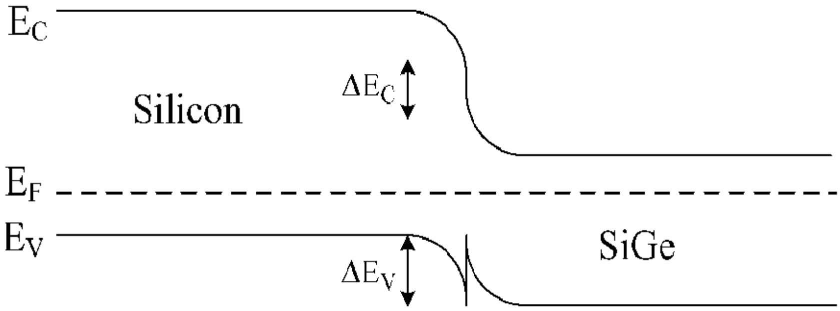

Figure 18. Energy band structure between different layers (Diaz, 2009)

As it is clear in this figure, the most difference of band gap can be seen in the Conduction band layer. For this reason, the movement of the holes from between the channel to Window junction is easily done because in this situation, the barrier height does not have much resistance. By converting the transistor to parasitic bipolar transistor, the breakdown voltage is reduced and by applying ionization, electron-hole pairs are formed. In fact, the effectiveness of the SiGe window depends on the germanium injection and the increase in its depth (Figure (19)). The greater the depth of this SiGe window, the better control of the impact of ionization.

The breakdown voltage increased with changes in window depth up to $1.2\mu m$ but after that, the breakdown voltage does not improve. The reason for this is related to the characteristics of the depletion area, which does not change with increasing the depth of the window. So, it can be concluded that the SiGe bipolar transistor is considered as a suitable candidate for working in improper environmental conditions and in space, because it has a high resilience capacity against radiation and not only has a low cost, but also has a great integrity capacity. The simulation results with improved performance and increased carrier lifetime for a SiGe bipolar transistor are shown in Figure (20).

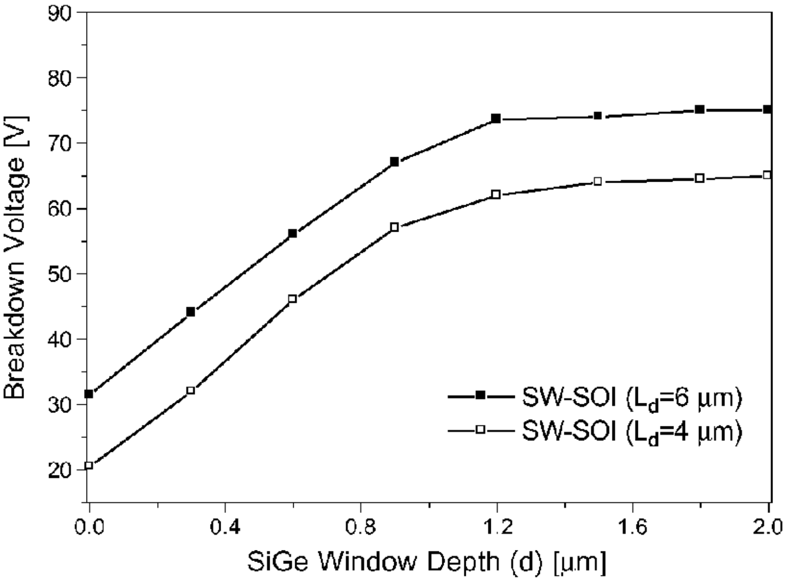

Figure 19. Break-down voltage of BJT vs. SiGe depth (Diaz, 2009)

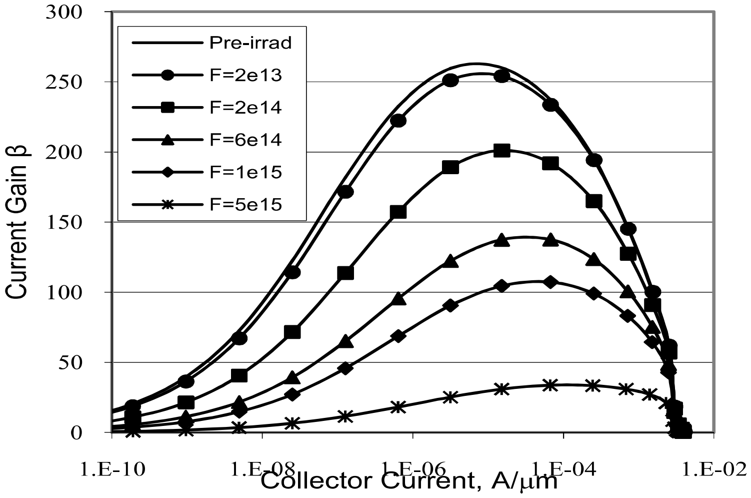

Figure 20. Variation of collector current vs. neutron fluences (Diaz, 2009)

E. Impedance Control for Noise Reduction

The parameters related to noise in high frequency applications need to be modeled and carefully checked in order to match the noise with the impedance of the transistor. In this situation, the main and influential parameters include F_{min}, R_n, R_{opt} and X_{opt}, the relationship between them are expressed in Equations (3-17) to (3-20) (Orouji & Mehrad, 2011). In this regard, there are several solutions to reduce the noise in the operation of transistors which consists of reduction in F_{min} , R_n and $\left|Y_s - Y_{opt}\right|^2$. As it is clear from the Equation (3-18), F_{min} is a function of ω_t and by increasing the cut-off frequency, the value of F_{min} can be reduced, which of course also increases the power consumption.

$$\mathrm{F} = F_{min} + \frac{R_n}{G_u} . \lceil Y_s - Y_{opt} \rceil^2 \tag{3-17}$$

$$F_{min} = 1 + \frac{2}{\sqrt{5}} \frac{\omega}{\omega_t} \sqrt{\gamma\alpha(1 - |c|^2)} \tag{3-18}$$

$$R_n = \frac{\gamma}{\alpha} \frac{1}{g_m} \tag{3-19}$$

$$Y_{opt} = G_{opt} + jB_{opt} = \frac{1}{R_{opt} + jX_{opt}} \tag{3-20}$$

$$Y_s = G_s + jB_s$$

Y_s : Source admittance

Y_{opt} : Optimal source admittance

γ : Noise coefficient

c : Correlation coefficient between two current sources

ω_t : Cut off frequency

F_{min} : Min. noise factor

R_n : Noise equivalent resistance

R_{opt} : Optimal resistance

X_{opt} : Optimal reactance

F. Ionization Effect on BJT Transistor

The layers designed for the Sic transistor is shown in Figure (21). To compare the designed structure on performance of the transistor, 3 different types of designs have been studied, which are shown in Figure (22).

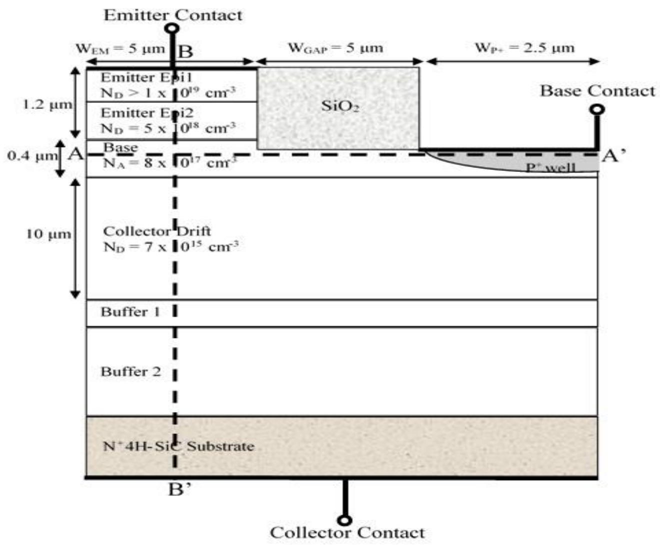

Figure 21. Cross-section of Sic BJT structure (Bouno & et al., 2010)

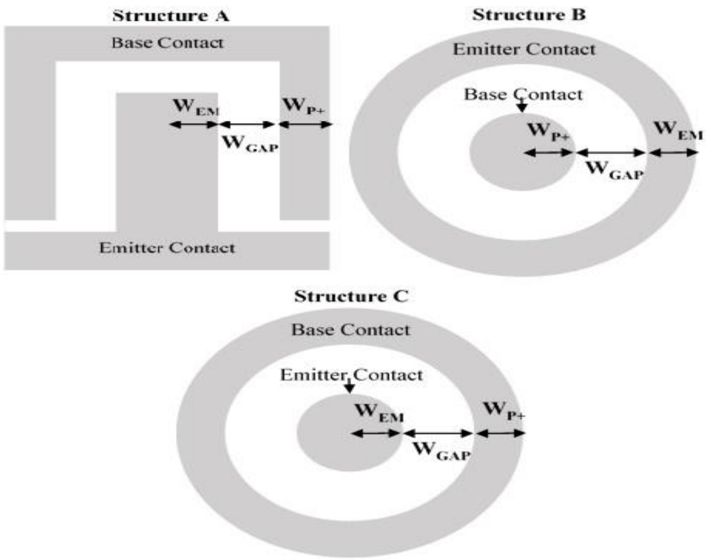

Figure 22. Top view of Sic BJT (Bouno & et al., 2010)

In plan A, rectangular geometry is used, and in plans B and C, circular geometry is used. As it is clear in the Figure (22), the central connection in design B is the base contact and in design C, is the emitter contact. The collector layer in this structure has a thickness equal to $10\mu m$ and in order improve its break-down voltage to be in the range of 2 kV, the amount of impurity injected into it is determined to be about $7 \times 10^{15}\ cm^{-3}$ (Dastgeer & et al., 2022). In Figure (23), the I-V curves are drawn in forward bias for all three designs.

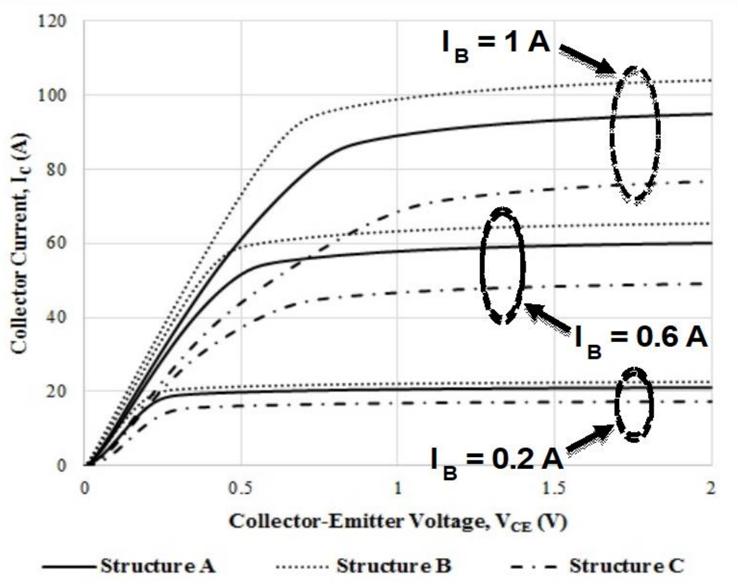

Figure 23. Variations of Ic Vs. VCE (Bouno & et al., 2010)

In this figure, the collector current (I_c) is plotted against the collector-emitter voltage (V_{CE}). In Figure (24), the changes of current gain (β) based on collector current (I_c) are also displayed.

G. Effect Of Emitter Width on Current Gain in On-State Condition

Current gain variations based on the increase in emitter width is shown in Figure (25). The max. amount of current gain in this condition is also shown in Figure (26). As can be seen, with the increase of the width of the emitter, the value of the current gain increases rapidly and after a certain value ($11\mu m$), it goes to the saturation state (Dastgeer & et al., 2022).

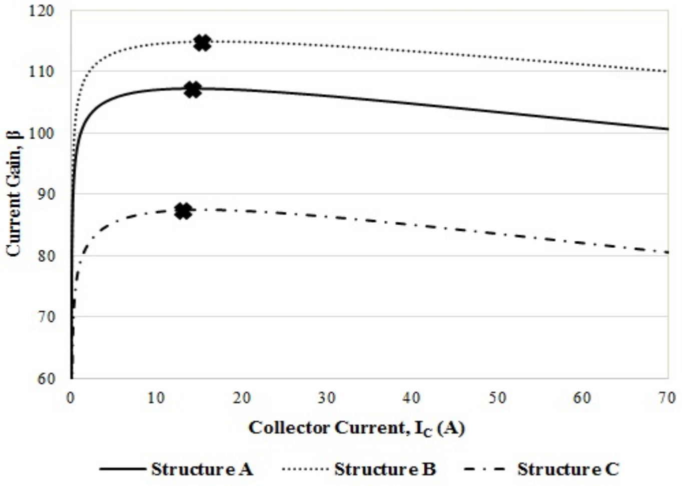

Figure 24. Variations of β Vs. I_c (V_{CE} = 5 V) (Bouno & et al., 2010)

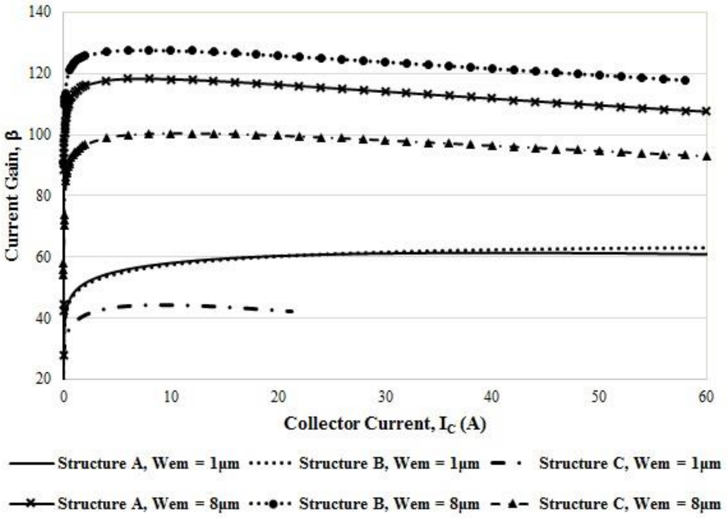

Figure 25. Variations of β Vs. I_c (V_{CE} = 5 V) (W_{EM} = 1 to 8) (Bouno & et al., 2010)

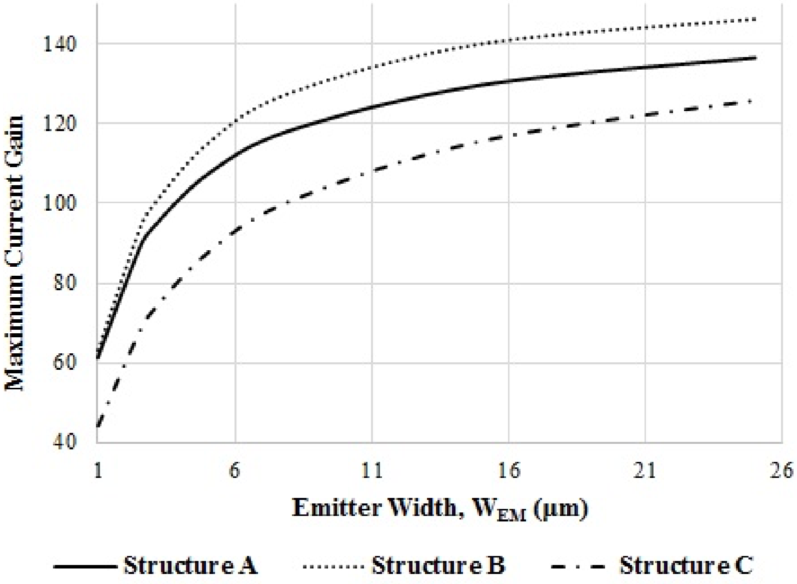

Figure 26. Variations of Max. β Vs. Emitter width (Bouno & et al., 2010).

In the on-state condition, the base current flows in the emitter region and causes a direct bias to be established in the base-emitter base and includes a limited voltage drop. If the amount of the emitter area becomes wider, the amount of forward bias in the B structure will increase, as a result of which the emitter current in this transistor will also increase (Figure (27)).

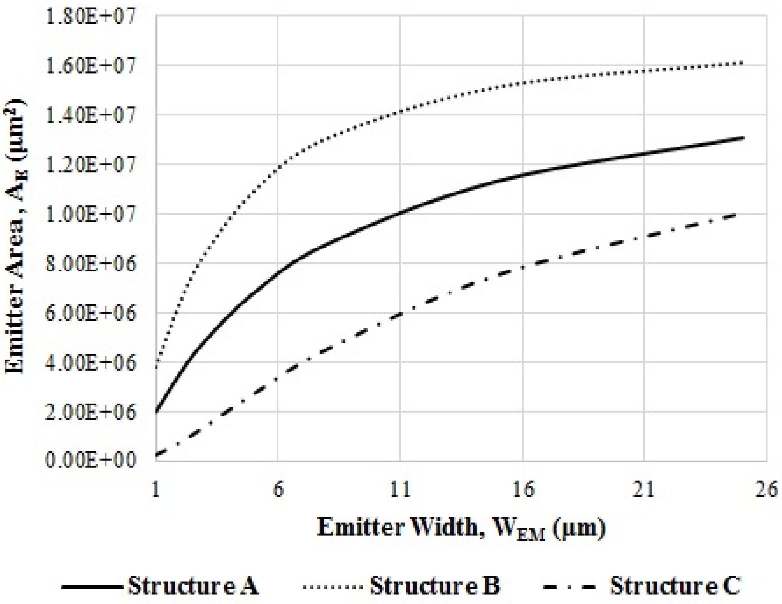

Figure 27. Variations of Emitter area Vs. Emitter width (Bouno & et al., 2010)

This has caused an increase in the emitter current in this section, which shows that the main current of the transistor is very dependent on the width of the emitter area. Among the three proposed structures, plan B includes the largest amount of current, and the sensitivity of this current to the area and perimeter of the emitter are shown in Figures (27) and (28), respectively.

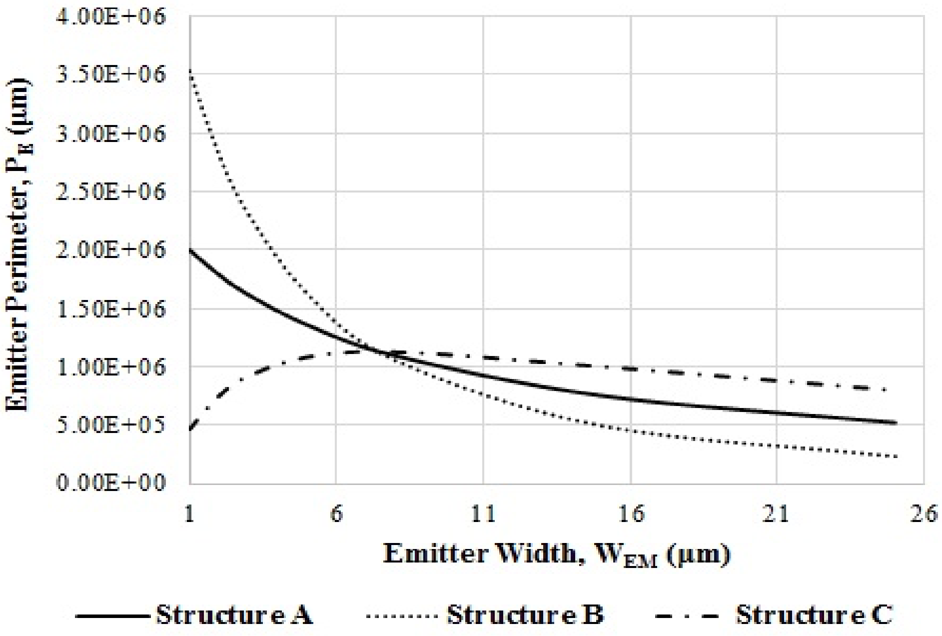

Figure 28.Variations of Emitter perimeter Vs. Emitter width (Bouno & et al., 2010).

IV. FINDINGS AND DISCUTION

A. P-N Diode

According to presented approach, if we know that the reverse current of this diode in the electronic circuit should not increase from 15 (μA), the BYV27 diode is proper choice. Also, the maximum reverse voltage that can be tolerated is in this diode is about 2 (v). If the BYV95 diode is used, the maximum reverse voltage that can be tolerated is about 4 (v), and if the 1N4007 diode is used, it can withstand voltages higher than 30 (v), because its maximum current at 30 (v) is about 10 (μA) Therefore, the changes of the reverse current damage constant (α) were obtained in terms of voltage, and the results are shown in Table (1) and Figures (29) to (31) are given.

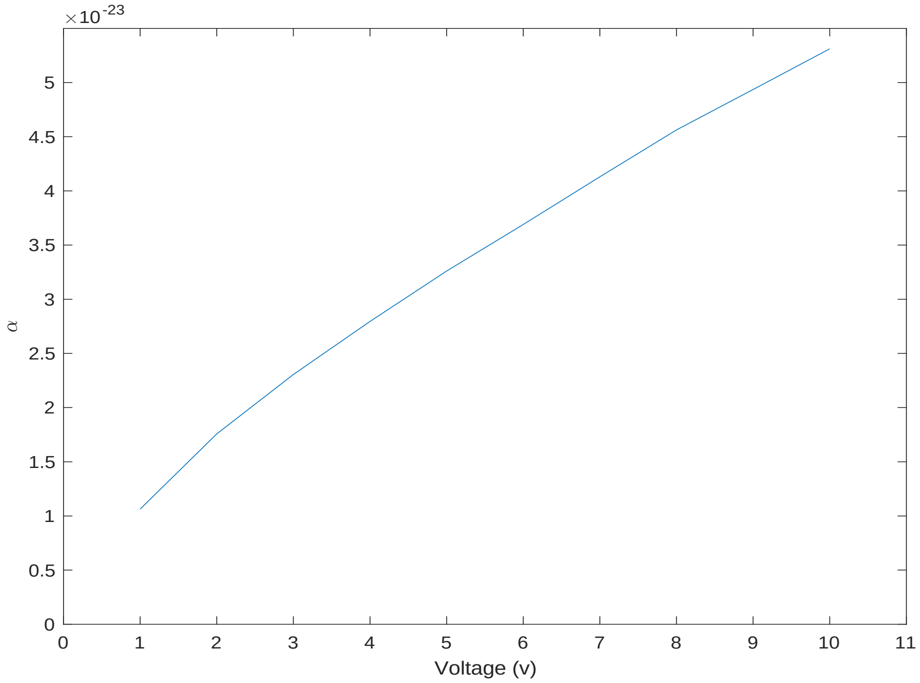

Figure 29. Variation of α vs. voltage for BYV27 diode

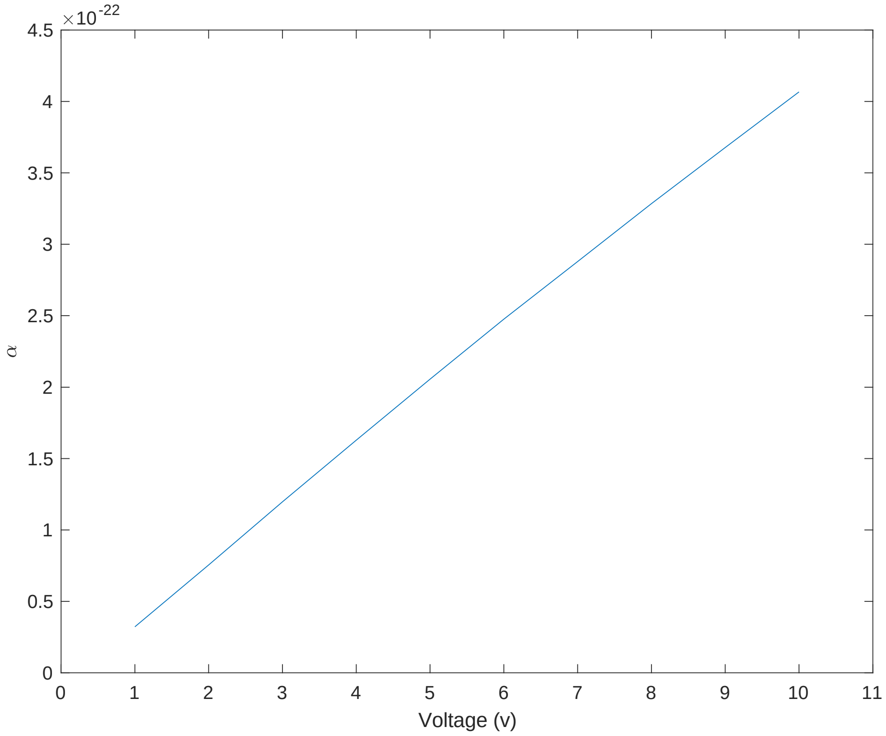

Figure 30. Variation of α vs. voltage for BYV95 diode

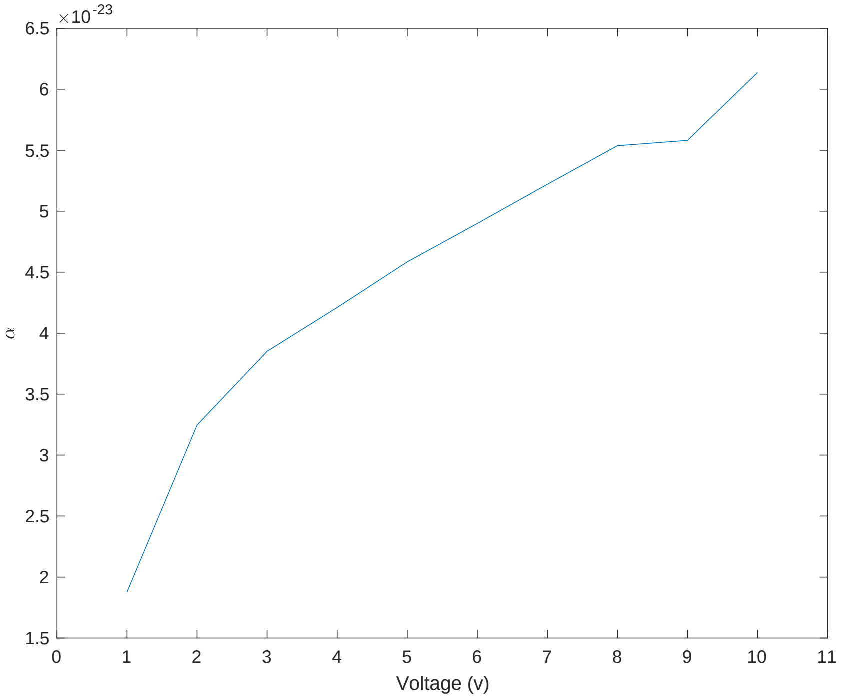

Figure 31. Variation of α vs. voltage for 1N4007 diode

Table 1. Comparison of reverse current constant (α) between different diodes

α	Diode		
(A.cm^2)	BYV27	BYV95	1N4007
1	$1/0630 \times 10^{-23}$	$3/2171 \times 10^{-23}$	$1/8777 \times 10^{-23}$
2	$1/7576 \times 10^{-23}$	$7/5474 \times 10^{-23}$	$3/2465 \times 10^{-23}$
3	$2/3056 \times 10^{-23}$	$11/97 \times 10^{-23}$	$3/851 \times 10^{-23}$
4	$2/7955 \times 10^{-23}$	$16/287 \times 10^{-23}$	$4/2103 \times 10^{-23}$
5	$3/261 \times 10^{-23}$	$20/56 \times 10^{-23}$	$4/5842 \times 10^{-23}$
6	$3/6901 \times 10^{-23}$	$24/755 \times 10^{-23}$	$4/8991 \times 10^{-23}$
7	$4/1305 \times 10^{-23}$	$28/791 \times 10^{-23}$	$5/2207 \times 10^{-23}$
8	$4/5624 \times 10^{-23}$	$32/846 \times 10^{-23}$	$5/5363 \times 10^{-23}$
9	$4/9361 \times 10^{-23}$	$36/775 \times 10^{-23}$	$5/5801 \times 10^{-23}$
10	$5/3106 \times 10^{-23}$	$40/671 \times 10^{-23}$	$6/1365 \times 10^{-23}$

If it is necessary that the reverse current of the diode at 2v voltage does not increase from 4 μA, then if the BYV95 diode is used, the maximum temperature that can be tolerated will be around $60^{\circ\mathrm{C}}$, and if the 1N4007 diode is used, the maximum temperature that can be tolerated will be around $40^{\circ\mathrm{C}}$. According to the temperature of the used environment, the appropriate diode can be selected. The changes of α according to temperature for BYV95 and 1N4007 diodes are listed in Table (2) and drawn in Figures (23) and (33).

Table 2. Comparison of reverse current constant (α) between different temperatures

$Temperature$	α	
(celcius)	BYV95	1N4007
$30^{\circ\mathrm{C}}$	$1/6 \times 10^{-23}$	$3/56 \times 10^{-23}$
$40^{\circ\mathrm{C}}$	$2/8 \times 10^{-23}$	$9/63 \times 10^{-23}$
$50^{\circ\mathrm{C}}$	6×10^{-23}	$1/79 \times 10^{-22}$
$60^{\circ\mathrm{C}}$	$1/54 \times 10^{-22}$	$3/3 \times 10^{-22}$
$70^{\circ\mathrm{C}}$	$1/59 \times 10^{-22}$	$3/33 \times 10^{-22}$
$80^{\circ\mathrm{C}}$	$1/6 \times 10^{-22}$	$3/35 \times 10^{-22}$

As can be seen, the reverse current damage constant α increases with increasing temperature, but at high temperatures this increase is very slow and insignificant. The reason for this is that at high temperatures the number of carriers increases greatly.

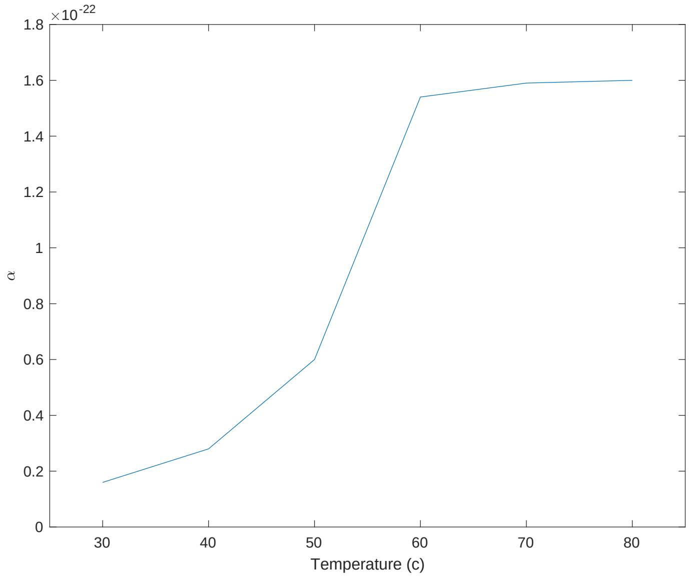

Figure 32. Variation of α vs. temperature for BYV95 diode

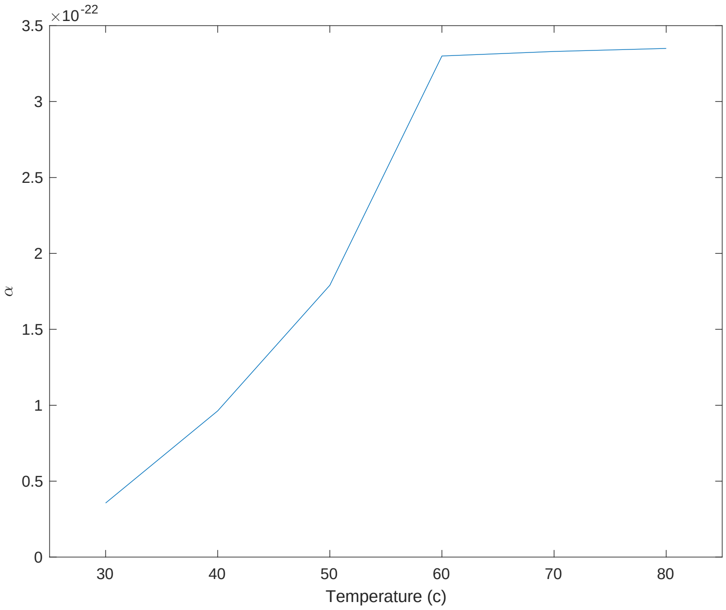

Figure 33. Variation of α vs. temperature for 1N4007 diode

B. Schottky Diode

1. Effect of Annealing Temperature

Through experimental tests, it has been proven that the Schottky diode (model Al/p-Si) which is made at room temperature (25℃) has not good quality, not fully rectified and its reverse saturation current is high. Therefore, these diodes were annealed for 5 minutes in a furnace in the temperature range of 100℃ to 300℃ and the corresponding I-V curves were measured and compared. The experimental results obtained from the simulation of annealing operation at temperatures of $100^{\circ\mathrm{C}}$, $200^{\circ\mathrm{C}}$, $250^{\circ\mathrm{C}}$, $300^{\circ\mathrm{C}}$ and $350^{\circ\mathrm{C}}$ are shown in Figure (34). As it is clear from the results, the semi-logarithmic changes of current-voltage are linear in the range of 0.2(v) to 0.4(v), and with the help of it, the reverse saturation current, the ideal factor and the Schottky barrier height can be obtained. It is necessary to explain that the semi-logarithmic graph of current-voltage is not linear at voltages higher than 0.5(V) and is related to the resistance value of the diode series (R_s) (Güler & et al., 2009). Table (3) shows the values obtained for ideality factor, Schottky barrier height and reverse saturation current. From the comparison of the results, it is clear that the minimum reverse saturation current occurs as a result of annealing in the temperature range of $250^{\circ\mathrm{C}}$ to $300^{\circ\mathrm{C}}$, and in this temperature range, proper rectification of the sample can be seen.

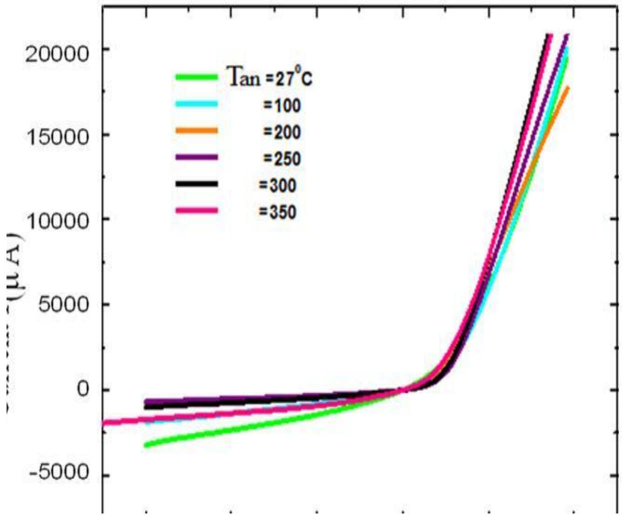

Figure 34. Semi-logarithmic curve of Schottky diode current-voltage

On the other hand, as the annealing temperature increases, the Schottky barrier height and the ideal factor increase. Therefore, the optimal annealing temperature is $250^{\circ\mathrm{C}}$, which is similar to the results obtained in (Nuhoğlu & Gülen, 2010). The increase in ideal factor with increasing annealing temperature can be explained by increasing the density of intermediate charges (Wang et al., 2003). Also, as the annealing temperature increases, the penetration of Al atoms in the Si layer also increases and causes the nature of the connection to change from the ideal Schottky connection to an ohmic connection (Bagatin & Gerardin, 2018). Also, increasing the annealing temperature leads to an increase in the thickness of the inherent oxide layer at the metal-semiconductor interface. The mentioned factors increase intermediate states. This increase also leads to an increase in the recombination of carriers and because of that, the ideal factor also increases

Table 3. Characteristics of annealed Schottky diode at different temperatures

Annealing temperature T (℃)	Schottky barrier height φ_{Bo}(eV)	reverse saturation current I_o(A)	ideal factor n
100	0.640	5.34×10^{-4}	2.18
150	0.651	5.12×10^{-4}	2.24
200	0.665	8.80×10^{-5}	2.45
250	0.674	4.31×10^{-5}	2.58
300	0.681	2.47×10^{-5}	2.71
350	0.685	2.71×10^{-5}	3.02

2. Effect of Temperature Variation

As it is clear from the equations, the reverse saturation current and other characteristics of the Schottky barrier diode depend on the diode temperature, and therefore, to evaluate the effect of the temperature of the sample, modeling of the temperature controller and vacuum turbo pump to cool the samples in the temperature range of 15^k to 300^k is used. Figure (35) shows the measured current-voltage curve (I-V) of Schottky diode annealed at the optimal temperature of $250^{℃}$ under different temperature conditions.

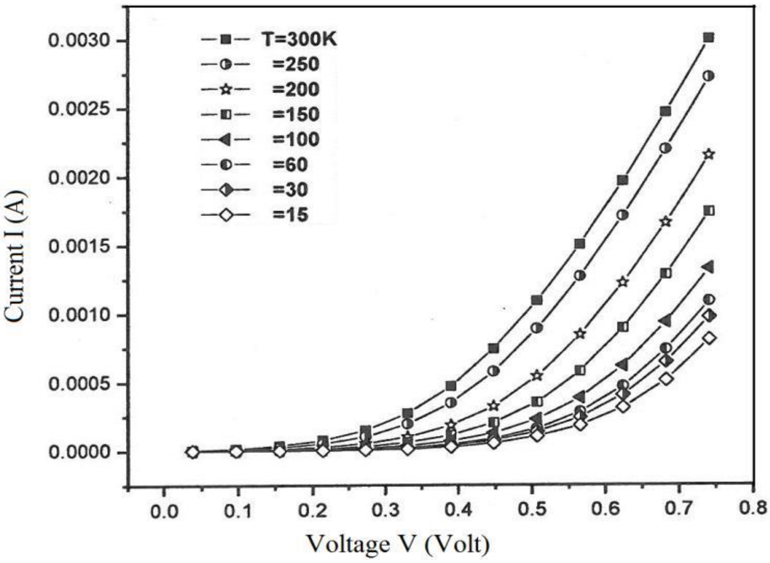

Figure 35. Semi-logarithmic curve of Schottky diode current-voltage

It is clear that with the decrease in the temperature of the diode, a sudden increase in the current at high voltage occurs, and this is due to its dependence on the ambient temperature. At this stage, the ideal factor (n) is extracted from the slope of the linear region of the semi-logarithmic characteristic of the current-voltage and similarly the reverse saturation current, by the width of the origin of the extrapolation line of its linear part (0.2(v) to 0.4(v)) and finally Using the obtained reverse saturation current, the Schottky barrier height is calculated and the results are listed in Table (4). As it is clear from the results, as the temperature of the sample increases, the ideal factor (n) decreases, but the Schottky barrier height at the interface φ_{Bo} increases.

Table 4. Characteristics of Schottky diode at different temperatures

Annealing temperature T (℃)	Schottky barrier height φ_{Bo}(eV)	reverse saturation current I_o(A)	ideal factor n
300	0.690	1.2×10^{-5}	2.5
250	0.56	2.55×10^{-6}	3.05
200	0.47	1.2×10^{-7}	3.62
150	0.34	6.4×10^{-8}	4.01

C. BJT Transistor

In this project, an NPN Transistor will be operated as a switch. The specification of used NPN transistor is given in the Table (5). In this regard, when $V_{IN} > 0.7$ V, the transistor acts as a short circuit.

Table 5. Characteristics of NPN transistor

Parameter	Value	Unit	Parameter	Value	Unit
α_I	100	-	q	1.1×10^{-19}	c
α_N	100	-	k	1.38×10^{-23}	$kg.m^2k^{-1}s^{-2}$
R_B	50	KΩ	V_{CB}	5	Volt
R_C	0.7	KΩ	V_{BE}	0.65	Volt
I_{E0}	0.1	mA	I_{C0}	100	mA

1. On-state Impedance Variations

a. On-state impedance vs.α_I

The variation of on-state impedance accordance to $\boldsymbol{\alpha_I}$ is shown in Figure (36).

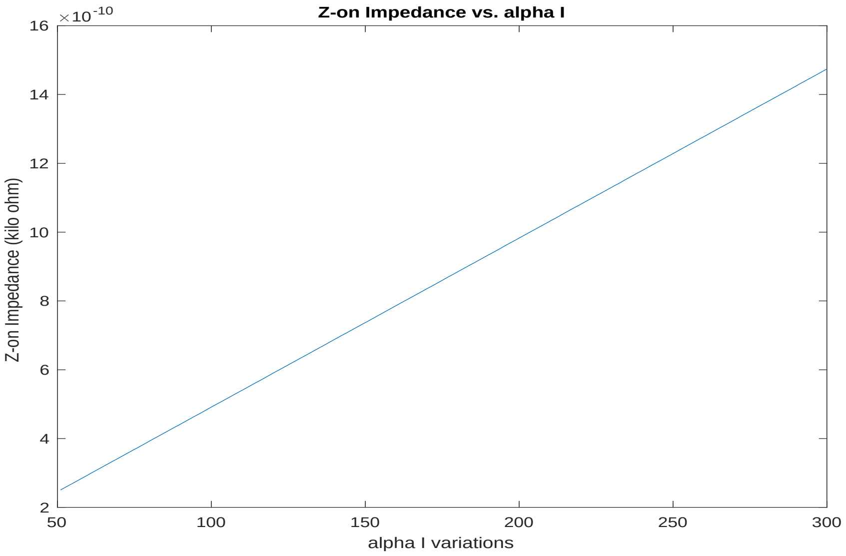

Figure 36. Variation of Z-on vs. α_I

In this condition, value of $\boldsymbol{\alpha_I}$ has changed from 50 to 300 and the value of on-state impedance has increased from 0.25 $\boldsymbol{\mu\Omega}$ to 1.47 $\boldsymbol{\mu\Omega}$. As it is clear in the Figure (36), the resistance of the transistor has increased. In other words, for each unit increase in the value of α_I, the resistance of the transistor increases 0.005 $\mu\Omega$.

b. On-state impedance variations vs. $\boldsymbol{\alpha_N}$

The variation of on-state impedance accordance to $\boldsymbol{\alpha_N}$ is shown in Figure (37). In this condition, value of $\boldsymbol{\alpha_N}$ has changed from 50 to 300 and the value of on-state impedance has increased from 0.238 $\boldsymbol{\mu\Omega}$ to 1.90 $\boldsymbol{\mu\Omega}$. The increase in the resistance of the transistor is greater than the increasing caused by the variation in the $\boldsymbol{\alpha_I}$ coefficient. In fact, the resistance of the transistor in the on-state mode is more sensitive to changes in the $\boldsymbol{\alpha_N}$ coefficient.

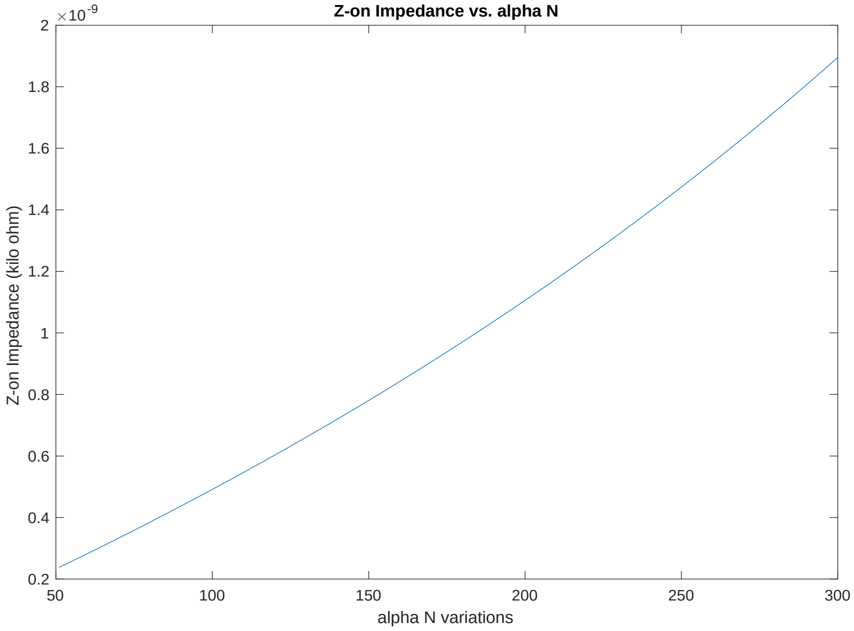

Figure 37. Variation of Z-on vs. α_N

c. On-state impedance variations vs. temperature

In this section, the impedance variations of the transistor in the active state with increasing temperature have been evaluated.

The temperature increased from 5° to 45° degrees and the amount of changes in such conditions is presented in Figure (38). As can be seen, the amount of changes can be ignored and in fact the increase in temperature cannot have a significant effect on the operation of the transistor in the on-state.

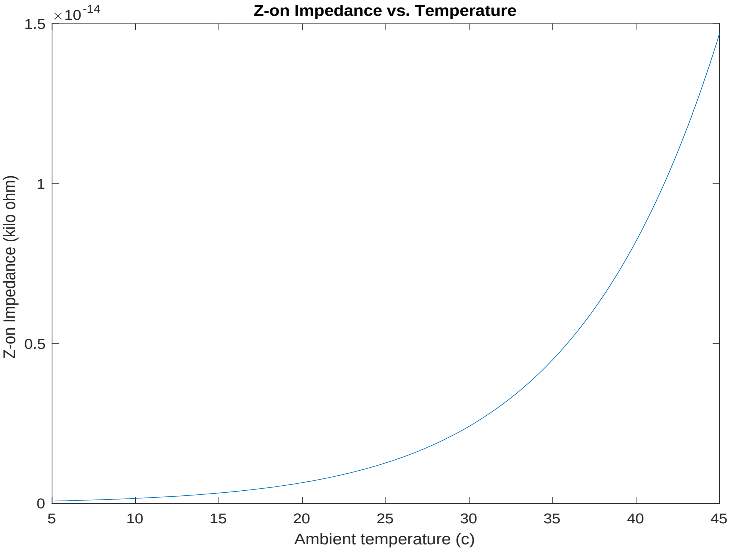

Figure 38.Variation of Z-on vs. Temperature

2. Off-State Impedance Variations

a. Off-state impedance variations vs. α_I

The variation of off-state impedance accordance to α_I is shown in Figure (39).

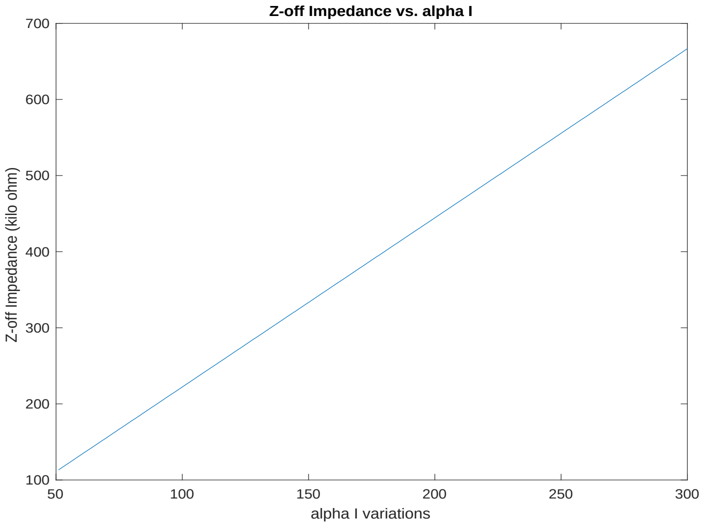

Figure 39. Variation of Z-off vs. α_I

In this condition, value of α_I has changed from 50 to 300 and the value of off-state impedance has increased from 113 **kΩ** to 667 **kΩ**. In this regard, increasing the coefficient α_I causes the resistance value of the transistor to increase up to 5 times. This means that by changing this parameter, it is possible to significantly increase the amount of impedance in the cut-off mode.

b. Off-state impedance variations vs. α_N

The variation of off-state impedance accordance to α_N is shown in Figure (40).

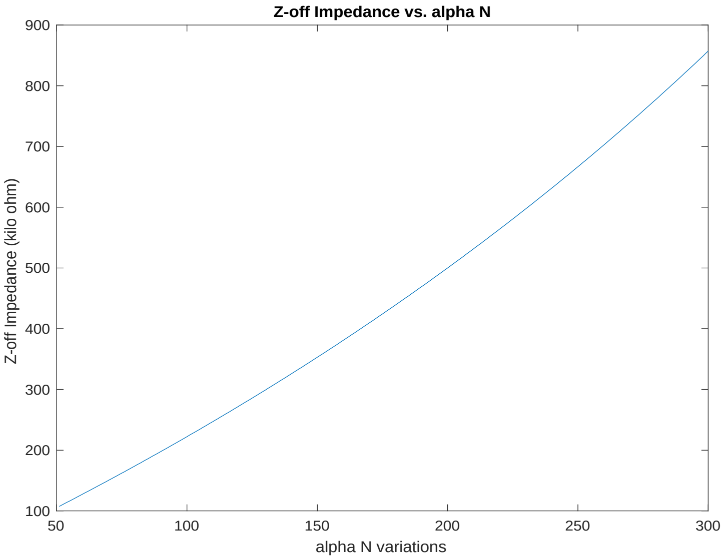

Figure 40. Variation of Z-off vs. α_N

In this condition, the value of $\boldsymbol{\alpha}_{\mathbf{N}}$ has changed from 50 to 300 and the value of off-state impedance has increased from 107 **kΩ** to 857 **kΩ**. In this regard, increasing the coefficient $\boldsymbol{\alpha}_{\mathbf{N}}$ causes the resistance value of the transistor to increase up to **7** times. This means that it is possible to significantly increase the amount of impedance in the cut-off mode**,** by changing this parameter.

c. Off-state impedance variations vs. temperature

In this section, the impedance variations of the transistor in the off state with increasing temperature have been evaluated. The temperature increased from 5° to 45° degrees and the amount of changes in such conditions is presented in Figure (41).

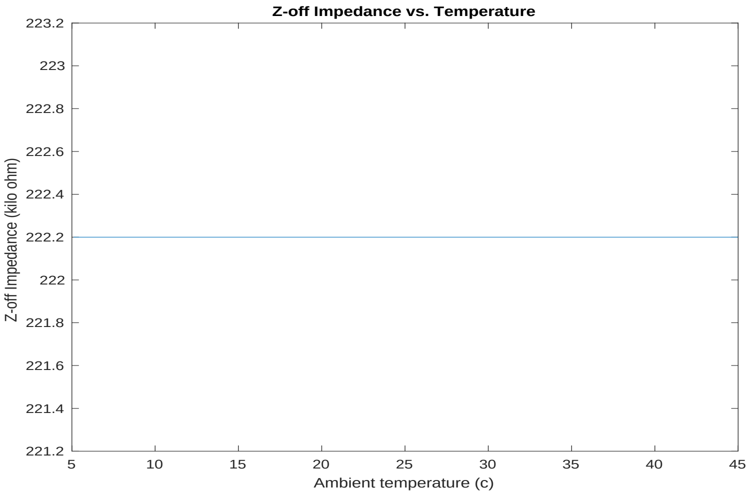

Figure 41. Variation of Z-off vs. Temperature

The obtained result shows that the impedance of the transistor in the off-state is not a depend on the temperature of the ambient and its increase/decrease cannot significantly change its value.

d. Off-state impedance variations vs. Vc

In the last case, the effect of changes of Vc on the off-state impedance has been investigated. As it is clear in the Figure (42), as the collector voltage increases from 1(v) to 20(v), the impedance also increases from 110 **kΩ** to 2200 **kΩ**.

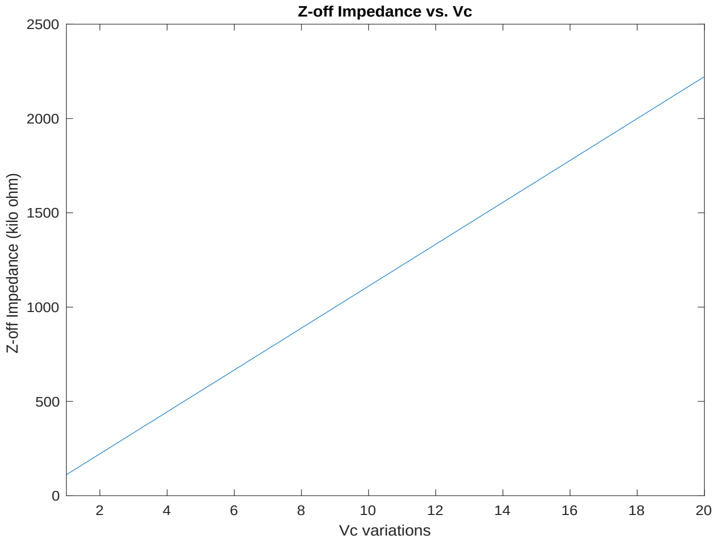

Figure 42. Variation of Z-on vs. Vc

As shown in Figure (42), the maximum value of the impedance variation in the off-state mode is related to the changes of collector voltage. In fact, with the increase of Vc, the impedance value of the transistor increases more than 20 times. This shows that by carefully controlling the value of it, the impedance range of the transistor can be controlled in a wide range.

V. RESULTS

According to obtained graphs, for on-state impedance the most effective factors belong to α_N, α_I and temperature, respectively. In other side, for off-state mode the most effective factors are collector voltage, α_N and α_I, respectively. It should be noted that the highest sensitivity obtained in the proposed approach is related to variation of V_C. So, with exact regulation of V_C, the off-impedance of transistor can be controlled properly. Also, we can admit that the reverse flow has a component that depends on the concentration of the synthesis and generation mechanism. As the concentration of synthesis increases, the reverse current constant (α) becomes larger, indicating that the part is more vulnerable. On the contrary, the smaller the reverse current constant (α) is, it indicates that the part is more resistant. Considering that the reverse current constant (α) is dependent on the reverse voltage and temperature, the most appropriate part can be selected for each application according to the ambient temperature and reverse voltage.

VI. CONCLUSION AND REMARKS

A. Conclusion

Electronic devices are made up silicon materials. The current mechanism inside silicon-based materials is a very crucial issue regarding the performance of the electronic devices. This thesis is based on micro-electronic research of the semiconductors.

With the expansion of electronic equipment in nowadays, using of transistors has also increased significantly. BJT transistors are still used as a vital element in the electronics industry due to their advantages such as low turn-on loss, proper durability and low maintenance price.

In this Work, evaluating the effect of various factors on the impedance in on-state and off-state of transistors can be very helpful to better control of their performance.

B. Conclusion Remarks

Electronic circuit parameters or impedance parameters are used to evaluate electrical quantities and determine the behavior of circuits. In a way, these descriptions relate electrical quantities in a circuit composed of interconnected elements. These approaches are widely used in microelectronic analysis. In this thesis, a mathematical model has been developed for on-state and off-state impedance in common emitter transistor circuits.

All these studies are applicated on an NPN Transistor while it`s operated as a switch. The obtained formulas were investigated using the MATLAB program. Then all the findings and the parameters affecting the open state and out-off-state impedance states are presented with the help of graphs. According to the findings, the variation of on-state impedance has changed, depending to the variation of each studied parameters. As it is seen, when increasing the values of each parameter then the value of on-state impedance has increased. As a result, the resistance of the transistor in the on-state mode is more sensitive to changes in related the coefficient of the transistor. Transistor current and voltage magnitudes can be correlated with the transistor parameters to be considered from both the transistor input circuit and the transistor output circuit. To summarize, different cases can be produced in this way, and the effects of transistor impedances and transistor characteristics can be examined.

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RESUME

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