QUANTUM DEVICE: EMPIRICAL MODELLING OF THE RESONANT TUNNELING DIODE

By

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List of Abbreviations

Abbreviation	Meaning
As	Arsenide
Al	Aluminium
AlAs	Aluminium Arsenide
AlGaAs	Aluminium Gallium Arsenide
AlSb	Aluminium
B	Boron
CMOS	Complementary Metal Oxide Semiconductor
DBQW	Double Barrier Quantum Well
DC	Direct Current
Ga	Gallium
GaAS	Gallium Arsenide
GaN	Gallium
GaSb	Gallium Antimony
GHz	Giga Hertz
IC	Integrated circuits
In	Indium
InGaAs	Indium Gallium Arsenide
InP	Indium Phospite
I-V	Current-Voltage
MBE	Molecular Beam Epitaxy
MOCVD	Metal Organic Chemical Vapour Deposition
N	Nitrogen
NDR	Negative Differential Resistance

PVCR	Peak to Valley Ratio
RTD	Resonant Tunneling Diode
Sb	Antimony
THz	Terahertz
V	Voltage
Vp	Peak Voltage
Vv	Valley Voltage
ZnSe	Zinc Selenium
Znte	Zinc Tellurium

Abstrak

Transistor telah digunakan secara meluas di dalam mereka bentuk litar bersepadu. Walau bagaimanapun, mengecilkan saiz transistor akan mempengaruhi prestasi peranti. RTD adalah peranti yang berkelajuan tinggi yang cekap dan memepunyai frekuensi tinggi sehingga Terahertz (THz) berbanding dengan transistor. RTD mempunyai potensi untuk menggantikan transistor di dalam peranti aplikasi frekuensi yang ultra tinggi pada masa hadapan. Selain itu, RTD beroperasi pada kuasa yang rendah berbanding dengan transistor. Penggunaan kuasa yang rendah perlu diambil kira di dalam reka bentuk litar bersepadu untuk peranti mempunyai prestasi dinamik yang tinggi. Kajian ini akan model dua jenis sistem bahan RTD iaitu GaAs/AlAs and $In_{0.8}Ga_{0.2}As/AlAs$ di dalam MATLAB menggunakan persamaan berasakan fizik dan membangunkan model litar di LT Spice IV. Model dan data eksperimen akan dipadankan secara empirikal di dalam MATLAB untuk memadankan model kepada eksperimen data. Dua kaedah telah digunakan untuk mensimulasikan model litar iaitu Simulasi Jadual dan Simulasi Polinomial. Padanan empirikal telah berjaya memadankan model kepada eksperimen data untuk GaAs/AlAs and $In_{0.8}Ga_{0.2}As/AlAs$ RTD. Simulasi Jadual telah berjaya simulasi ciri-ciri I-V eksperimen untuk GaAs/AlAs and $In_{0.8}Ga_{0.2}As/AlAs$ lebih baik daripada Simulasi Polinomial.

Abstract

The transistor was widely employed in integrated circuit design. Nevertheless, the continued scaling the transistor size will affect the device performances. RTD is an efficient high-speed device and has high-frequency operation up to Terahertz (THz) compared to the transistor. It has the potential to replace the transistor in the ultra-high frequency device applications in the future. Furthermore, RTD is a low power consumption device that works at low power compared to the transistor. Low power consumption needs to consider in integrated circuit design to have highest dynamic performance. This study will be modelled two different material system of RTD, which is GaAs/AlAs and $In_{0.8}Ga_{0.2}As/AlAs$. The physic-based equation will be simulated in MATLAB and the circuit model will be built up in LT Spice IV. Empirical fitting will be done in MATLAB to match the model to the experimental data. Meanwhile, in LT Spice IV, two methods were employed to simulate the circuit model, which are Table simulation and Polynomial simulation. The empirical fitting had been successfully matched the model to the experimental of GaAs/AlAs and $In_{0.8}Ga_{0.2}As/AlAs$. Based on results analysis, Table simulation had been successfully simulated I-V characteristics of experimental GaAs/AlAs and $In_{0.8}Ga_{0.2}As/AlAs$ better than Polynomial simulation.

CHAPTER 1

INTRODUCTION

1.1 Project Background

A diode is an electrical device which has two terminals known as anode and cathode. Generally, a diode, allowing current flow in one direction. Therefore, it can act as a switch. The P-N junction diode is an instance of the semiconductor device that allows the current flow in a single direction. There are many types of diodes presented such as Zener diode, Schottky diode, Photodiode and also Light Emitting Diode (LED). These diodes are widely used based on their applications in devices. For example, Zener diode has a unique characteristic which is operating in forward and reverse bias thus produces the stable reference voltage. Hence, it is widely used in power supplies. Resonant Tunneling Diode (RTD) which is also a powerful device that will be discussed in this study on its unique current-voltage characteristics.

Tunnel diode was also known as Esaki diode and discovered by Leo Esaki that reveals negative differential resistance in I-V characteristics and high-speed transient response [1]. Tunnel diode is experiencing the quantum tunneling; the current flow uses the concept of quantum mechanical particle tunneling, which beliefs the particle has both wave and particle properties. In typical physic, the particle can only pass through the potential barrier when the kinetic energy of a particle is higher than a barrier height.

While, in the quantum well, it is unique as the particle has wave-like properties which can pass through the potential barrier even when the kinetic energy of particle is lower than the barrier. The particles can tunnel through a very thin barrier and appear on the other side of the barrier in the quantum well. This behavior can be seen when a narrow band gap semiconductor was sandwiched in between two wider band gap semiconductors in heterojunction semiconductor.

Resonant Tunneling Diode is a device that had been through the process of quantum mechanical tunneling. Thus, it exhibits unique I-V characteristics and gives advantages in various digital design circuits. It will provide fast switching speed with a very low power consumption, which is beyond to CMOS circuits [2]. RTD operates when the current is switching the device and allowing the current to flow in the quasi-bound states which is a double barrier structure in the quantum well. The quantum well consists of the double barrier structure in between two doped contacts which are emitter and the collector.

This study is about modeling and simulating Resonant Tunneling Diode which has a unique current-voltage characteristic - a valley known as negative differential resistance. The peak to valley current ratio (PVCR) is an important parameter to attain a high dynamic performance of RTD [3]. The effect of DC characteristic parameter on RTD performance will be discussed in this study. The physic-based equation of RTD will be modelled and simulated in MATLAB. The empirical fitting will be carried out to fit the model with experimental DC characteristics. Both models and experimental data will be compared and analyzed. Two different types of semiconductor in RTD with the different material system known as GaAs/AlAs and $In_{0.8}Ga_{0.2}As$/AlAs will be used in this study to compare their DC characteristics. RTD model circuits will be constructed in the LT Spice IV to simulate current-voltage characteristics.

1.2 Problem Statement

CMOS technology was invented a long time ago in manufacturing an integrated circuit (IC) or chips and turning in the semiconductor industry. It is widely employed in digital logic circuits such as microcontrollers and microprocessors. However, the continually scaling size of the transistor will give effect on switching performance of the device [4]. Therefore, a resonant tunneling diode was introduced as an alternative to improve this issue. RTD provides negative differential resistance that causes it to have better speed performance in switching activity. Furthermore, the fabrication process is much faster [2]. RTD has proved that it possesses a maximum frequency of 1.46 THz [5] compared to CMOS that has a maximum frequency of 215 GHz [3]. This high-speed switching is useful for wideband communications and imaging system applications [3].

Apart from high-speed performance, low power consumption is also an important parameter in constructing an integrated circuit. Low power consumption will provide high dynamic performance devices. Resonant tunneling diode offering low power consumption compared to CMOS. Hence, this makes RTD a demanding device in inventing the most advanced electrical device in the future [2]. RTD is device with features of ultra high- frequency with low power consumption. Thus, RTD is a more convenient device in high-speed digital circuits and broadband communications applications [6].

The performance of the RTD can be determined by analyzing the DC characteristic parameters. These parameters can be extracted from I-V characteristics. Peak to current ratio (PVCR) is an important parameter in determining the speed of the device. PVCR is influenced by peak current density and valley current density. In addition, negative differential resistance must be sharp for high PVCR; thus providing a high dynamic range [7]. These DC characteristic parameters will be discussed in details. The modeling and simulation of the device will optimize the performance and identify the behavior of the device. The behavior of the I-V characteristics can be seen when the parameters of the physic-based equation was being modified during modelling.

1.3 Project Objectives

This work is a study on the I-V characteristics of the resonant tunneling diode. The objectives of this project were as follows:

1. To model and simulate the physic-based equation of the resonant tunneling diode to determine the current-voltage characteristics of the device in MATLAB
2. To fit the current-voltage characteristic of the resonant tunneling diode of physic-based model to experimental data by empirical fitting
3. To develop a circuit model and simulated I-V characteristics of resonant tunneling diode in the LT Spice IV

1.4 Project Scopes

The project was conducted within the following specifications:

1. The resonant tunneling diode will be modelled and simulated to study the current-voltage characteristics of the device at room temperature (300 K).
2. Two different types of material system semiconductor RTD will be modelled and simulated.
3. The model and experimental DC characteristics will be empirically fit by changing the parameters of physic-based equation.
4. The circuit model of RTD will be developed and simulated in the LT Spice IV to obtain the I-V characteristics

1.5 Thesis Layout

This thesis is organized into five chapters. The first chapter would discuss the project background of resonant tunneling diode, problem statements, project objectives and also project scopes.

Chapter 2 is the literature review of the thesis. The previous work on resonant tunneling diode will be discussed in this chapter. It stated the problem statement and methodology on the previous journals that have been studied as references to complete this study.

Chapter 3 is about the methodology of the thesis. This chapter describes how to model and simulate RTD model and analyze I-V characteristics. Empirical fitting will be discussed in this chapter for comparing models and measured data. Besides that, developing a circuit model of RTD in LT Spice IV will also be explained in this chapter.

Chapter 4 is about the result and discussion. This chapter contains the results of modelling and simulation of RTD using MATLAB and its current-voltage characteristics. The empirical fitting result for both model and measured data will be discussed in this chapter. Besides that, an RTD circuit model which was developed and simulated in LT Spice IV will also be discussed in this chapter. Chapter 5 concludes all the results that have been gathered. Some suggestions for the future improvement will be stated in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Since early as two decades, the diode has been invented. In earlier invention, the diode is only recognized as a two terminal device that allowed current to flow in one direction. Significantly, this makes the diode works as a logic switch. Nowadays, there are varieties of diodes introduced as their usefulness is widely advanced. Among the equipment that used diode are those that are used to detect high-frequency electromagnetic waves and to convert sunlight into electricity. Nevertheless, this study will be focused on a diode which advanced in the high-speed and high-frequency application known as the resonant tunneling diode (RTD). RTD has a unique DC characteristic that has peak and the valley that will form a negative differential resistance region [2].

Resonant tunneling diode has features of high-speed, low-cost and very dense, which are useful for further growth of solid state technology in the future [6]. Thus, resonant tunneling diode is a preferable nanoelectronic device due to its unique characteristics of negative differential resistance that gives many advantages to the high-speed and high-frequency applications. RTD was widely used in digital applications such as analog to digital converter [8], wideband communications and imaging system [3].

Since the tunnel diode was invented two decades ago, it draws attention to many researchers. They are studied for modeling the device, fabrication process, theoretical device and also applications. Besides that, DC characteristics of the RTD are also an important criterion in determining the device performance as it was widely studied in the presented works. There are many factors which influenced the RTD performance and it can be identified based on its I-V characteristics. Hence, this study is to model and simulate the I-V characteristic of the RTD of two dissimilar types of material system semiconductors.

2.2 Band Discontinuity

This section will discuss on heterostructures of semiconductor that will form a double barrier quantum well and band discontinuity of lattice matched. Band discontinuity is referring to changes in band edges at both valence band and conduction band when two materials that have different band gaps in contact. Band discontinuity is an important factor that will determine the properties of electrical and optoelectronics devices. A further explanation on band gap discontinuity will be discussed in the next section.

2.2.1 Heterostructures

Each semiconductor has different band gap, work function, electron affinities and dielectric constants. A Heterojunction is formed when two different semiconductors with different band gap energy, but closely lattice matches were merged together [9]. Generally, one semiconductor will have a wider band gap while another one will have a narrow band gap. Heterostructures are formed when more than one heterojunctions are present, which afford properties that are useful for high-speed and high-frequency device applications [10]. This is due to heterojunction is capable of controlling electron and hole carrier transport itself.

There must be abrupt changes at band edges when energy carriers pass through the heterojunction interface. Abrupt changes in heterojunction interface form when a wider band gap has extra electron and have a tendency to cross into the narrow band gap [11]. This condition gives benefits to the device properties. The electrical and optical properties of heterojunction are depending on this discontinuity of conduction and valence band energies at its interface.

Figure 2-1 illustrates the energy band discontinuity of two semiconductors with different band gaps before contact and after contact. From Figure 2-1, there are abrupt changes in the interface of the junction when both semiconductors have merged together. During formation of the junction, the electron will diffuse from N-type semiconductor to the P-type semiconductor while holes will diffuse to the P-type to the N-type semiconductor. This results in increment of depletion region and formation of curvature of the energy bands.

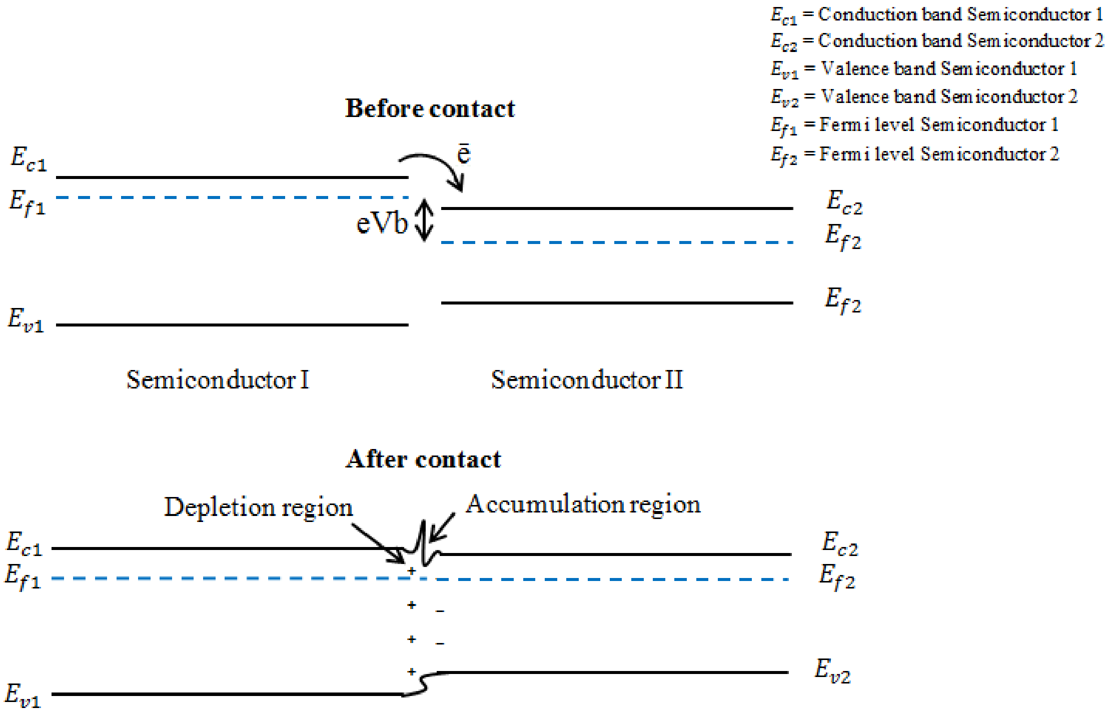

Figure 2-1: Energy Band Diagram when two different band gap energy of semiconductor before contact and after contact [12]

E_{c1} and E_{c2} are the conduction band for Semiconductor 1 and Semiconductor 2 respectively, while E_{v1} and E_{v2} are valence band; Semiconductor 1 and Semiconductor 2 respectively. E_{f1} and E_{f2} presenting the Fermi level for both semiconductor 1 and semiconductor 2. From Figure 2-1, Semiconductor 1 has a wider band gap while semiconductor 2 has a narrow band gap. Band gap discontinuity can be evaluated in between the conduction band and the valence band of both semiconductors as shown in (2-1) [13].

Band gap discontinuity:

$$\Delta Eg = \Delta Ec + \Delta Ev \quad (2\text{-}1)$$

where,

$$\Delta Ec = E_{c1} + E_{c2} \quad (2\text{-}2)$$

$$\Delta Ev = E_{v1} + E_{v2} \quad (2\text{-}3)$$

An epitaxial growth crystal is grown by heterostructures that were formed by merging a narrow band gap and wider band gap semiconductor. Invention in epitaxial crystal growth will lead to advanced optoelectronics devices [14]. Epilayer that consist of heterostructures are grown by either Metal Organic Chemical Vapor Deposition (MOCVD) or Molecular Beam Epitaxy (MBE) techniques [15]. This study used an experimental RTD model which was grown by MBE techniques.

2.2.2 III-V Compound Semiconductor

Semiconductor was divided into the groups of binary, ternary and quaternary semiconductor based on the alloy composition. Commonly, resonant tunneling diode was developed in III-V heterostructures material systems [16]. High-speed heterostructures device of III-V compound semiconductor are based on epitaxial layer sequences which must include heterojunctions and doping modulation [17]. The III-V compound semiconductor is the preference for resonant tunneling diode structure. The ability to devise the band gaps of this material for improving the mobility of electron and thus, provides higher current density is the reason it was chosen [13]. Table 2-1 indicates the elements from group III and V in Periodic Table.

Table 2-1**:** Elements from Groups III and V in Periodic Table

Group III	**Group V**
B	N
Al	P
Ga	As
In	Sb

The III-V heterojunction has offered some advantages; efficient in device performance, insensitive to the temperature and also the capability to fabricate [11]. In the early years, GaAs, AlGaAs, and InGaAs are among compound semiconductor from the III-V group material which widely used in optoelectronics devices [14].

2.2.3 Lattice Matched

Band gap discontinuity can be devised to the device characteristics and behaviors by having flexibility in controlling the transporting of electrons and holes across heterostructures. However, the material pair needs to be carefully considered to avoid the disturbance at the interface of the heterojunction as it may cause the broken bond. The material pair must be a very close lattice in lattice constant to ensure the growth is simpler and obtain a well epitaxial crystal structure throughout the layers [15]. There is some lattice matching which has nearly equal lattice constant with a different band gap, such as GaAs, ZnSe and AlAs and Znte, GaSb and AlSb [18]. Figure 2-2 shows Energy Gap versus Lattice Constant for most common ternary III-V compound semiconductor. The solid line indicates direct bandgap while the dashed line indicates indirect bandgap.

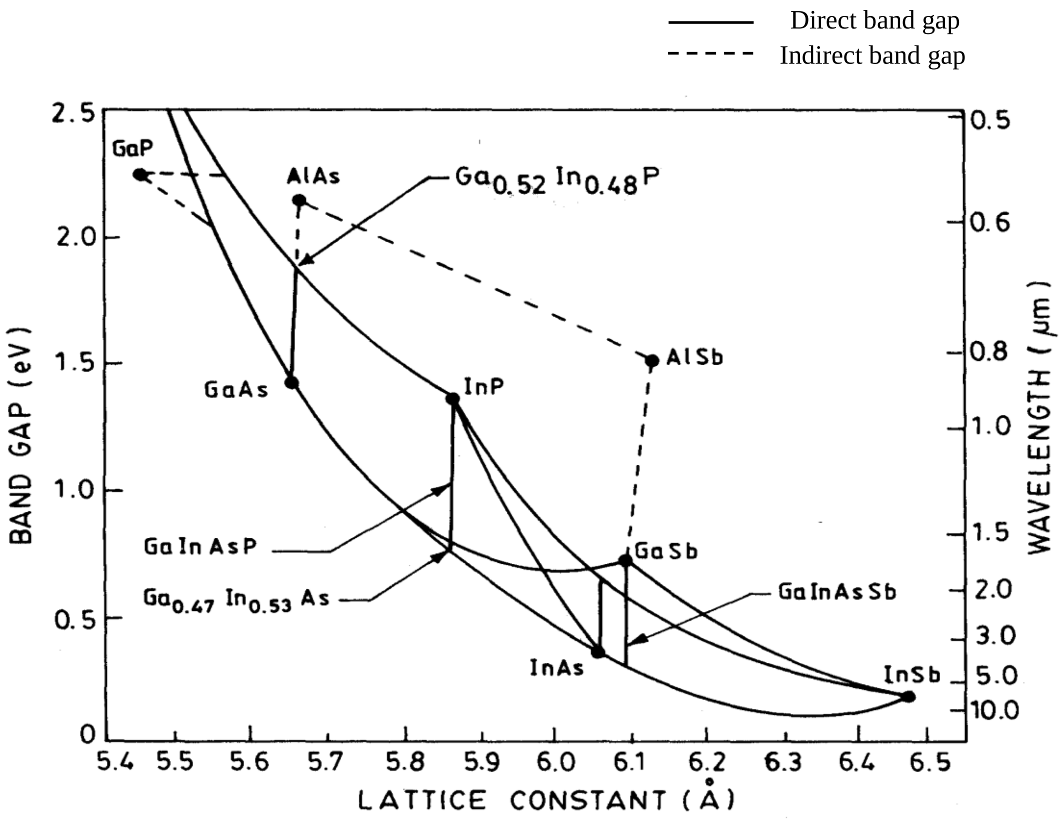

Figure 2-2: Lattice Constant III-IV Semiconductor [19]

Lattice matched is defined as material systems that have almost similar lattice constants of the epitaxial layer and substrate [14]. As shown in Figure 2-2, GaAs and AlAs are definitely closed lattice matched which is less than 0.2 percent difference in lattice constant. The merged of GaAs with any of $Al_xGa_{1-x}As$ alloy will become a single crystal with no defect at its interface [11]. The direct bandgap of $Al_xGa_{1-x}As$ and GaAs may possible, but the bandgap must vary between 2.79 eV to 1.51 eV by changing the value of x. Another example close lattice matched of III-IV material that was developed excessively recently is $In_xGa_{1-x}As/Al_yIn_{1-y}As$ layers that are lattice matched to InP as a substrate. This structure does not require composition grading to avoid the dislocation defect in the device [9]. $In_{0.53}Ga_{0.47}As$ and $Al_{0.48}In_{0.52}As$ are other examples of ternary semiconductor which its lattice matched to InP. Table 2-2 depicts the valence band offset of lattice matched forming heterojunction structures.

Table 2-2: Valence Band offset in Heterojunction

Heterojunction Material	**ΔEv (eV)**
GaAs/ $Al_xGa_{1-x}As$	0.46x
GaAs/AlAs	0.31
GaAs/InAs	0.35
AlAs/ $Al_{0.37}Ga_{0.63}As$	0.34
AlAs/InAs	0.35
InP/ $Ga_{0.47}In_{0.53}As$	0.32
GaAs/AlSb	0.40
GaSb/ $InAs_{0.95}Sb_{0.05}$	0.67
GaN/AlN	0.7±0.24
AlN/GaN	0.57±0.22
InN/AlN	1.81±0.2
InN/GaN	1.051
$Al_{0.48}$In0.52As/ $Ga_{0.47}In_{0.47}As$	0.75
GaSb/InAs	0.51
AlN/InN	1.32±0.14
$Ga_{0.5}In_{0.5}P$/GaAs	0.32

When two dissimilar materials come into contact, there will be an abrupt change at the interface between these lattices. Mismatched between these lattices will caused by crystalline defect that is the dislocation of the atom. Dislocation will increase electron-hole recombination rate, and causes non-radiative recombination [9]. The electron and holes may trap in the dislocation state and affect the properties of the devices. This will reduce the performance of the device by having poor electrical properties. Although lattice mismatched can cause dislocation problem in the lattice, it can also reduce the strain by controlling the growth. Strain energy increase as the thickness of material increase. Therefore, the critical thickness concept in the lattice matches was introduced in semiconductor development to help in avoiding dislocation problem.

2.2.4 Material System

The closed lattice matched material system from group III-V compound semiconductor was widely manufactured for many years ago [16]. Among the material systems from III-V compound semiconductor that was used in the quantum well structures are GaAs/GaAlAs, GaSb/GaAlSb, InGaAs/InAlAs and InGaAs/AlAs [15] where GaAs, GaP GaSb, InP, InAs are the common substrates used [9]. There are many material systems used in developing Resonant Tunneling Diode (RTD) to optimize the performance of the device. GaAs/AlGaAs with a quantum well thickness of 5 mm and barrier layer of 1.5 mm to 5 mm thick was working in [3]. The theory of the RTD operation and optimization tradeoff between peak current density and barrier thickness was discussed in this study.

In [20] four different structures of GaAs/AlAs have been investigated. They discussed the effect of quantum well and barrier thickness on current-voltage characteristics of the RTD. The result indicates peak voltage is involved by the quantum well thickness while peak current is affected by barrier thickness. In addition, other work had focused on AlAs/GaAs/AlAs material system [10]. They reported the effect of barrier thickness and spacer length on current-voltage characteristics of the RTD. Meanwhile, in [21] the effect of electron launcher structures on GaAs/AlAs double barrier RTD has been examined. They reported the achievement of getting the peak current density of 170 kA/cm^2 and peak to valley current ratio (PVCR) of 3.2.

The convenient physic-based equation for current-voltage characteristics of Resonant Tunneling Diode was introduced in [22]. They were models $In_{0.53}Ga_{0.47}As$/AlAs Resonant Tunneling Diode (RTD) and InAs/AlSb/GaSb Resonant Interband Tunneling (RIT). They found the band bending would give large effect when spacer layer are wide with small doped. The proposed equation was considered band bending in total depletion approximation. The voltage drop over collector layer was included for a more realistic result. InGaAs/AlAs double barrier RTD in InGaAlAs optical waveguide has been studied in [23]. They introduced an electro-absorption of modulated light that achieved 1500 nm wavelength.

Besides that, the effect of scattering at the heterojunction interface on I-V characteristics of InP-based RTD has been discussed. They have utilized the material system of InGaAs/AlAs and InGaAs/InAs [10]. In [24] the effect of growth interruption on electrical and optical properties of AlAs/ $In_{0.53}Ga_{0.47}As$/InAs RTD has been discussed.

RTD oscillator was successfully invented in [25] which can achieve frequency from 100 GHz to 712 GHz, operating at room temperature by using InAs/AlSb material system. Meanwhile, [26] had proposed composition double barrier that consists of InAIN/GaN/InAIN replacing AlGaN to eliminate piezoelectric polarization in heterojunction structure. Despite they are many material system were demonstrated at high peak current density, but mostly RTD works well in GaAs substrates due to maturing growth process and device process technique [21]. Hence, this study will use the material system of GaAs/AlAs and $In_{0.8}Ga_{0.2}As$/AlAs RTD which has matured growth process for conventional RTD.

2.3 Quantum Well

RTD has undergone the process of quantum tunneling phenomena via double barrier quantum well. Quantum well is formed when a narrow of band gap semiconductor is sandwiched in between two wider band gap layers. The wider band gap layer is known as the barrier while a narrow band gap is known as a well in double barrier quantum well structure.

Figure 2-3 illustrates double barrier quantum well structure in nanometer dimensions. It consists of two heavily doped contacts which are region I, II, VI and VII with a small band gap, for example, GaAs. Region I and II present the emitter while region VI and VII present the collector of quantum well. Regions III and V are both the barrier which has wider bandgap, such as AlGaAs. Region IV is the quantum well, which also has small bandgap.

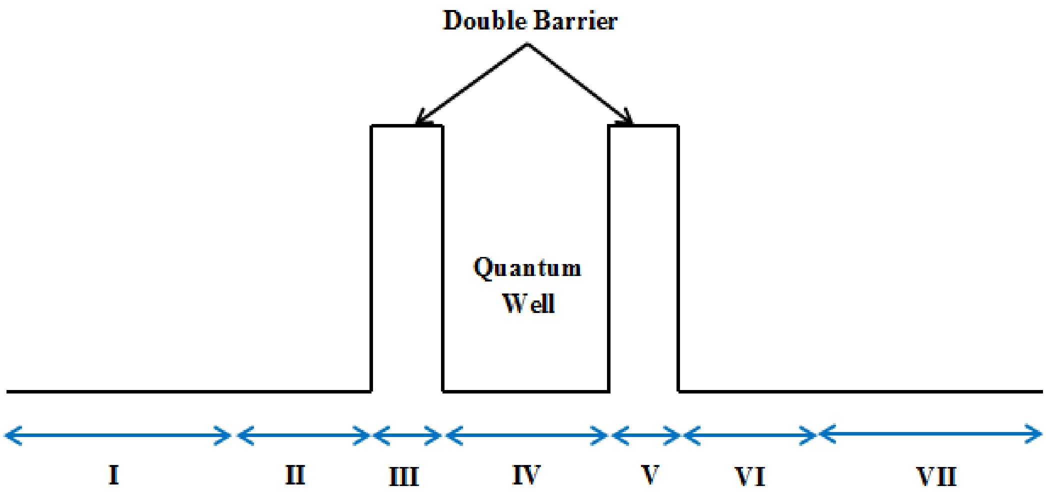

Figure 2-3: Physical process of double-barrier tunneling [27]

The important criterion for quantum well is transporting the electron across the double barrier when the bias voltage applied. This structure resembles the characteristics of electron wavelength that leads to the quantum phenomena such as tunneling and quantization states [27]. This has caused resonant tunneling occurs in a double barrier quantum well structure. The molecular beam epitaxy (MBE) is usually used for the growth of the double barrier of RTD due to its ability to control the thickness layer literally and composition of alloy [20].

There are two types of tunneling mechanism; interband tunneling and intraband tunneling. Interband tunneling is electrons flowing from the conduction band to the valence band or holes flowing from the valence band to the conduction band. P-type and N-type doping are required for this mechanism. Conversely, intraband tunneling is when electrons flowing from one conduction band to another conduction band or holes flowing from one valence band to another valence band. This mechanism only required either N-type or P-type doping. In this study, the focus is in the intraband tunneling.

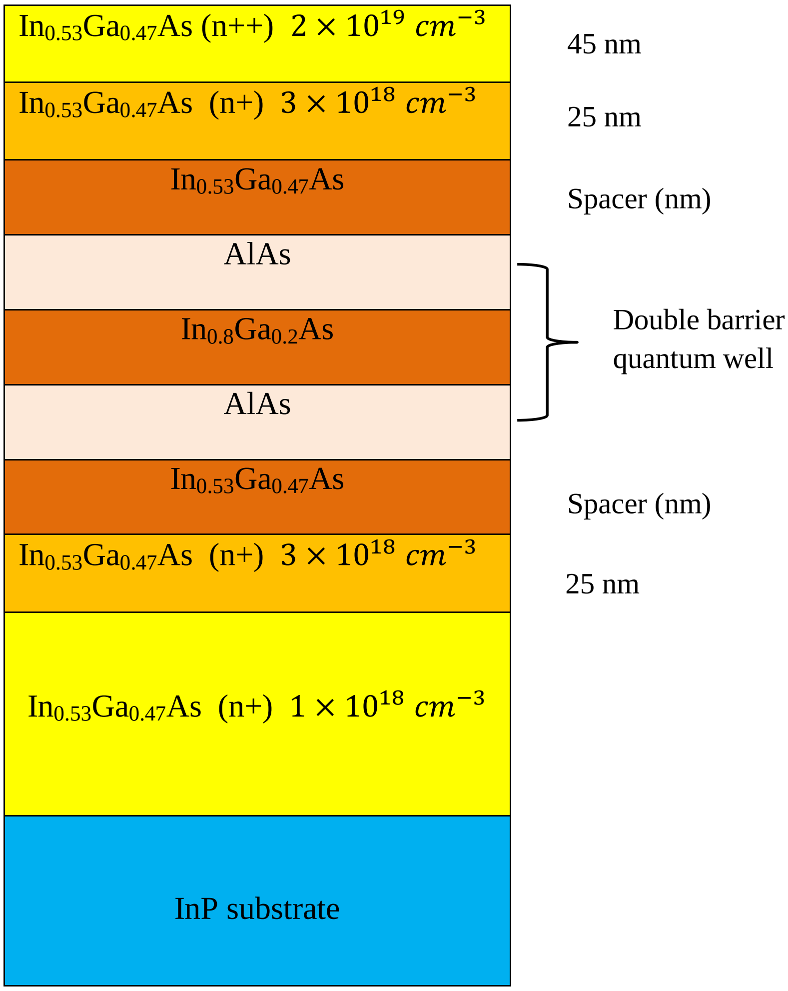

Figure 2-4: $In_{0.8}Ga_{0.2}As$/AlAs double barrier structure [13]

Figure 2-4 is shown an example of the double barrier structure of InGaAs/AlAs RTD that will be used in this study. The barrier layer is formed from AlAs meanwhile, the quantum well formed by $In_{0.8}Ga_{0.2}As$. The other layers are $In_{0.53}Ga_{0.47}As$ lattice-matched to InP substrate. This epilayer structure grown in molecular beam epitaxy (MBE) is widely used in nanoelectronics device fabrications [17].

2.4 Resonant Tunneling Diode

The active layer of RTD consists of undoped quantum well sandwiched between two undoped barrier layer. This structure creates quasi-bound states related to the resonant tunneling mechanism. The double barrier layers are connected to the emitter and collector contacts which are heavily doped. Tunneling mechanism of RTD gives many advantages for high-speed applications compare to CMOS [3]. Among the invented quantum tunneling device technology, the quantum effects of the RTD devices have been a concern for researchers to study due to the capability of RTD to operate at high frequency with low power dissipation. This section will discuss on the principle operation of RTD and its unique I-V characteristic which is negative differential resistance (NDR) that has brought RTD to the demanding high-speed device in the recent years.

2.4.1 Principle of Operation

RTD used a quantum mechanical tunneling concept that allows electron penetrates through the barrier which is very thin compared to the de Broglie electron wavelength. Figure 2-5 will demonstrates the classical view that electrons must have sufficient energy to cross the barrier, or else it will bounce back. However, in quantum mechanical view, the electron behaves like particle-wave duality and allowed electron across the barrier [28]. The green portion of the curve shows that thicker barrier has small probability the electron can be seen on the other side of the barrier compared to a thinner barrier that has large probability electron found in the other side of the barrier.

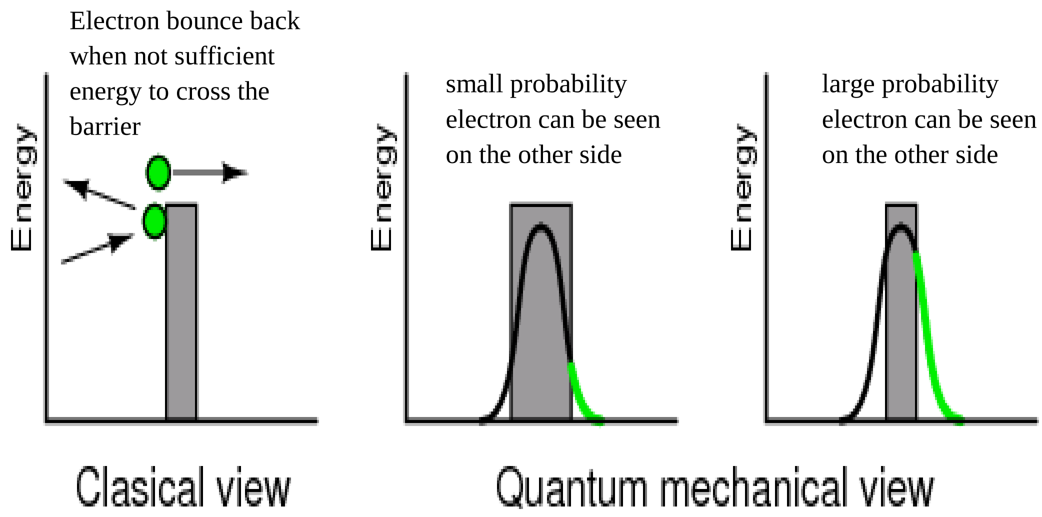

Figure 2-5: Quantum mechanical tunneling [28]

Initially, when there is no applied bias voltage, the diode is thermal equilibrium and the Fermi level is in the constant state. When the forward bias voltage applied, the electrons will flow through a tunnel barrier from an emitter to collector. The quasi-bound energy causes the electrons flow through the tunnel well. As the electron energy increase with the quasi-bound state due to the increasing amount of applied voltage, more electrons will flow through the tunnel well to the collector.

However, when the energy level of the electron is equal to the energy level of the quasi-bound state, the current reaches a maximum. When the more voltage applied, this will cause the currents to reduce as the electrons obtained too much energy. Somehow, the current is increasing again due to substantial thermionic emission [3]. This will allow electrons pass through the non-resonant energy level. As the result, it will form a valley current that can be considered as leakage current. Figure 2-6 illustrates the process of electron passes through the double barrier quantum well and generates I-V characteristics of RTD.

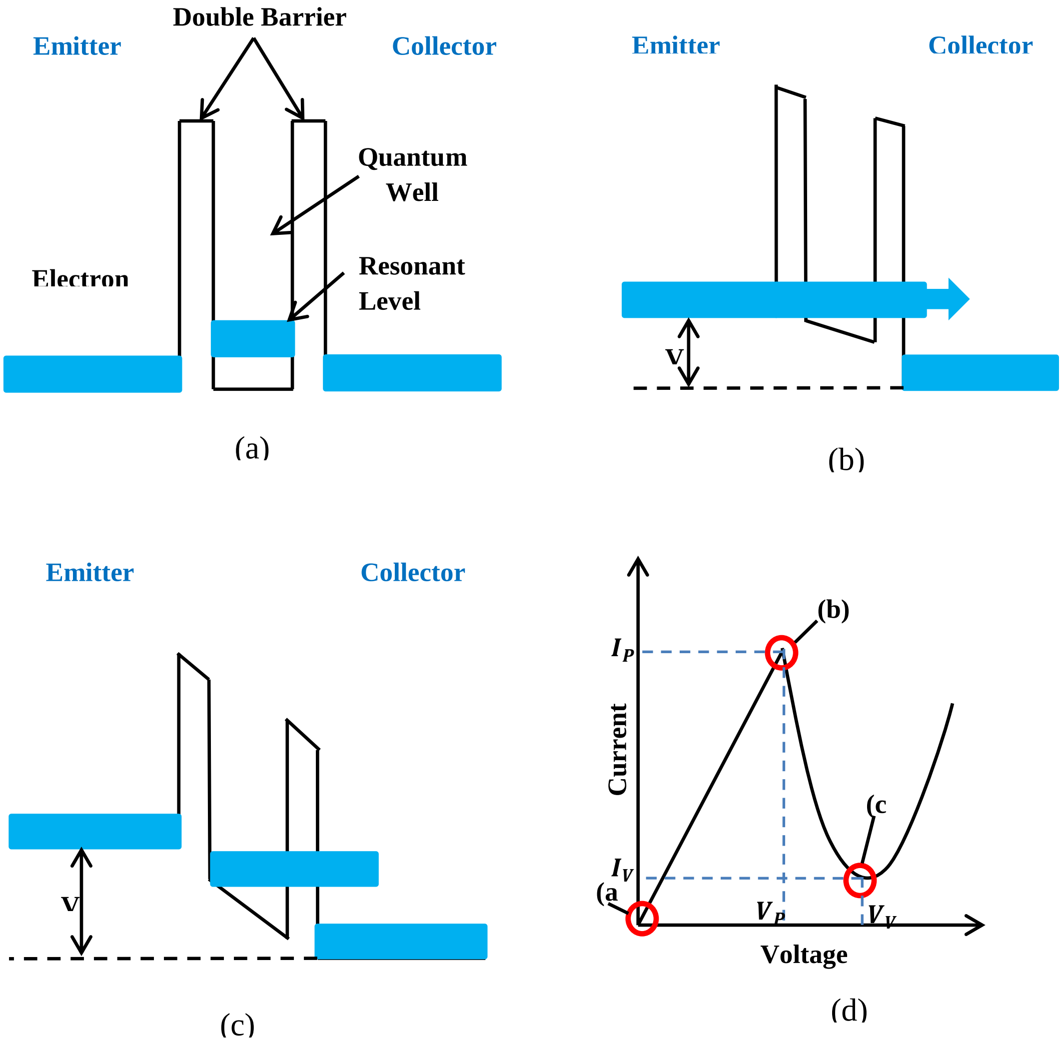

Figure 2-6: I-V Characteristics of RTD corresponding to electron passes through the quantum tunnel well. (a) zero bias (V= 0), (b) resonance (V= Vpeak), (c) off-resonance (V=Vvalley) and (d) I-V characteristic of RTD [29]

2.4.2 Current – Voltage Characteristics

Resonant tunneling diode has negative differential resistance (NDR) in I-V characteristics due to the effects of tunneling in semiconductor [13]. NDR occurs when there is a transverse momentum conversion condition in epitaxial growth crystal. NDR formed in I-V characteristics when there are no electrons in the emitter can pass through the quantum well during the conservation of transverse momentum. This will lead to sharp decreasing the current density from its maximum value [27]. NDR influences the speed and the frequency of the device. Sharp NDR will lead to high-speed and high-frequency devices. High frequency is regarding to the small value of device capacitance, hence, have high frequency operation. Equation (2-4) can find the approximation of device capacitance [13].

$$C_d = \frac{A\varepsilon_o \varepsilon_r}{t} \tag{2-4}$$

Where A is the area of the device. ε_o and ε_r are presenting the permittivity of free space and the relative permittivity of the barrier and well materials. t is the thickness of the double barrier quantum well structure that consists of the layer of the spacer, barrier and well. Resonant Tunneling Diode is a nanometer device which has nanometer thickness layers. This resulting very small capacitance, thus, has high- frequency devices.

Furthermore, the NDR properties were given advantages in digital circuit design. NDR properties will lead to reducing the complexity in the logic circuit [30]. It has the ability to create a bistable or multistable circuit and switching between two stable states can be very fast [31]. Meanwhile, in [26] they have validated the NDR characteristics of InGaN/InAIN/GaN/InAIN RTD. They have found that greater NDR can be obtained when uses the In composition in $In_xGa_{1-x}N$ is around 0.06. Furthermore, a sharp negative differential resistance will offer a low power consumption of the resonant tunneling diode. Consequently, it will reduce the static and dynamic power dissipation during switching or without switching operations.

In addition, peak to valley current ratio (PVCR) is an important parameter since the performance of the resonant tunneling diode depends on the peak to valley current ratio. High peak current density will has efficient performance of RTD. High PVCR indicates the device has high-speed transient response. High-speed transient response is very useful in high-speed switching applications. Apparently, the equation (2-5) denoted that I_P must be large in order to get high PVCR [13]. Nevertheless, too large peak current will have a large power dissipation. I_P and I_V are presenting the peak current density and valley current density respectively.

$$\text{PVCR} = \frac{I_P}{I_V} \tag{2-5}$$

Figure 2-7 shows general I-V characteristics of RTD which exhibits negative differential resistance region. J_P, J_V, V_P and V_V are peak current, valley current, peak voltage and valley voltage respectively.