INVESTIGATION ON THE DC CHARACTERISTICS OF THE RESONANT TUNNELING DIODE THROUGH EMPIRICAL MODELLING

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by

TAN KER LEE

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LIST OF ABBREVIATIONS

AlAs	Aluminium Arsenic
CMOS	Complementary Metal-Oxide-Semiconductor
DBRTD	Double Barrier Resonant Tunnelling Diode
GaAs	Galium Arsenic
GHz	Gigahertz
InAs	Indium Arsenic
InGaAs	Indium Galium Arsenic
InP	Indium Phosphide
I-V	Current-Voltage
NDR	Negative Differential Resistance
PVCR	Peak-to-Valley Current Ratio
RTD	Resonant Tunnelling Diode
THz	Terahertz
VLSI	Very-Large-Scale Intergration

ABSTRACT

Double Barrier Resonant Tunnelling diode (DBRTD) is a two-terminal electronic device that employs the principal of quantum mechanics. The working operation is tunnelling electrons through a barrier at certain energy level in resonant state. In term of quantum mechanics, the particles behave as wave-particle form. In this research work, the working principle, theories, structural parameters as well as the current-voltage (I-V) characteristics specialised in Negative Differential Resistance (NDR) need to be studied through empirical modelling with curve fitting using MATLAB simulation tool and physics equations. RTD is specialising in presenting the I-V relationship in NDR region that opposes the nature Ohm's law as the relationship is inversely proportional in the simulated curve. This special feature characteristic however enables an ability to generate a high speed frequency up to Terahertz. For the empirical modelling, device physical dimensions can be identified after the unknown parameters are determined through I-V curve fitting in MATLAB simulation. Mainly, the research is focus on two device structures, GaAs/AlAs labelled as XMBE#66 and InGaAs/AlAs labelled as XMBE#230. GaAs/AlAs modelled peak current density of 16290 A/cm^2, peak voltage of 0.315 V, valley current density of 4294 A/cm^2, and valley voltage of 0.422 V. InGaAs/AlAs modelled peak current density of 39820 A/cm^2, peak voltage of 0.305 V, valley current density of 4447 A/cm^2, and valley voltage of 0.685 V. In short, InGaAs/AlAs device would be able to give higher performance than GaAs/AlAs with a higher Peak-to-Voltage Current Ratio (PVCR) of 8.954 while PVCR of GaAs/AlAs with a lower PVCR of 3.794. The potential development of DBRTD would be unexpectedly great as the future high end technologies and electronics high speed applications replacing the current conventional diodes.

ABSTRAK

DBRTD merupakan satu elektronik peranti dua-terminal yang mengaplikasi kuantum mekanik. Operasi kerjanya adalah menerowong electron melalui satu halangan peranti pada satu peringkat tenaga dalam keadaan resonant. Dalam konteks kuantum mekanik, partikel bertingkah laku dalam bentuk gelombang. Dalam kerja penyelidikan ini, prinsip operasi, teori, struktur parameter serta ciri-ciri I-V khusunya dalam bidang perbezaan rintangan negatif perlu dikaji melalui model empirical dengan penyesuaian lengkungan menggunakan alat simulasi MATLAB dan penyamaan fizik. Keistimewaan RTD dalam menyampaikan hubungan arus-tegangan dalam bidang NDR yang menentangi sifat Ohm's law kerana hubungan tersebut adalah berbanding terbalik dalam lengkungan simulasi. Walaubagaimanapun, ciri-ciri khas ini membolehkan keupayaannya untuk menjana frekuensi kelajuan yang tinggi sehingga Terahertz. Bagi model empirical, dimensi fizikal peranti boleh dikenalpasti selepas parameter yang tidak diketahui ditentukan melalui penyesuaian lengkungan I-V dalam simulasi MATLAB. Singkatnya, kajian ini menumpukan kepada dua struktur peranti utama, iaitu GaAs/AlAs yang melabelkan XMBE#66, dan InGaAs/AlAs yang melabelkan XMBE#230. GaAs/AlAs dimodelkan kepadatan puncak arus 16290 A/cm^2, voltage puncak 0.315 V, lembah ketumpatan arus 4294 A/cm^2, dan lembah voltan 0.422 V. InGaAs/AlAs dimodelkan kepadatan puncak arus 39820 A/cm^2, voltan puncak 0.305V, lembah ketumpatan arus 4447 A/cm^2, dan lembah voltan 0.685 V. Pendek kata, peranti InGaAs/AlAs akan dapat memberikan prestasi yang lebih baik daripada GaAs/AlAs dengan PVCR yang lebih tinggi sebanyak 8954, manakala PVCR GaAs/AlAs lebih rendah sebanyak 3794. Pembangunan potensi DBRTD akan manjadi sebaiknya dengan teknologi akhir tinggi masa depan dan elektronik aplikasi berkelajuan tinggi menggantikan diod konvensional arus.

CHAPTER 1: INTRODUCTION

1.1 Research Background

Till today, the processing of information technology is moving towards a higher speed, lower costing and more compact fashion accordingly. New electronic devices which keen for smaller and faster integrated circuit such as memory technology in computer industry and applications, keep on going to meet the demand of the market globally. Intel Moore's law states that, each single chip density will be doubled for every two years and this has been true over the past decades as the demand for smaller ICs are increasing continuously and leading the market to the growth of nanotechnology which is very crucial for the manufacturing of VLSI ICs. One of the major concern in today's integrated circuit with respect of design and development is speed, the speed of processing. Up to date, Complementary Metal Oxide Semiconductor (CMOS) has been operating high speed up to Gigahertz (GHz). This speed is however insufficient to support the future technology, therefore a higher operating frequency device is needed for the future development of technology. Many researchers and scientists have been conducting experiments and tests actively to resolve the solution for the device that is able to operate in higher frequency range and not failing the processes at the same time.

Double Barrier Resonant Tunnelling Diode (DBRTD) is a two terminal active device, found by Esaki and Tsu, invented after the junction tunnel diode, also known as Esaki diode by Leo Esaki in 1957 [1]. DBRTD is a device that is able to operate high frequency up to Terahertz (THz) compared to other conventional transistors [2]. It is a latest device that shows a significant improvement in device operating speed, and thus offers a wide range of applications in electronics industries such as environmental monitoring, medical imaging, radio astronomy and telecommunications [3]. The highest room temperature fundamental oscillation of up to 1.31 THz was achieved and demonstrated by Professor Masahiro Asada, Tokyo Institute of Technology using thin-well RTDs made of InGaAs/AlAs [3].

Resonant Tunnelling Diode (RTD) is an electronic device based on the principle of quantum mechanics. Unlike the normal conventional diode, RTD electrons can tunnel through a barrier or well at certain energy level and further working principal will be explained in the following chapters. The application of quantum mechanics is one of the factors driving the improvement on the operating frequency of the device. In DBRTD physical structure, two thin barriers with two highly doped electrode terminal at both ends sandwiches a quantum well, and the tunnelling mechanism takes places between two barriers [4].

Negative differential resistance (NDR) is one of the most significant characteristic of RTD. According to Ohm's law, current and voltage is directly proportional to each other, i.e. the voltage increases while the current increases or vice versa. This means that RTD opposes the nature Ohm's law of current-voltage (I-V) relationship by existing NDR region whereby the voltage increases as the current decreases. This special characteristic leads to RTD ability of generating continuous wave (CW) at high frequency of Terahertz and growing interest in RTD device for many researchers [5]. Progressing to this report, the work is focus on the peak voltage, peak current density, peak to valley current ratio, the negative differential resistance, and how the RTD performs by the parameters and limitations on the physical structure.

A wide range of characteristics can be produced by the engineering of tunnelling structure in DBRTD. These characteristics includes barrier width, bandgap energy, barrier height, space thickness, concentration of doping and the quantum well width. Therefore the design of DBRTD device is flexible as well as the development stages. InGaAs/AlAs and GaAs/AlAs are the examples of DBRTD devices. They are composed of group III and V semiconductor elements which have nearly matched lattice constant [6].

InGaAs/AlAs and GaAs/AlAs will be the focus of my research with InGaAs and GaAs as the quantum well, while AlAs as the barriers. The bandgap energy differences are engineered so that the quantum well has material of lower bandgap energy while barriers consists material of higher bandgap energy. The physical parameters of the devices will be determined and adjusted to fit the corresponding current-voltage relationship curve.

1.2 Problem Statement

Two-terminal resonant tunnelling diode is the fastest electronic device as it can produce a high frequency up to Terahertz (THz) range. A RTD device can provide a frequency of about 1.31 THz by double barrier InGaAs/AlAs RTD. Today, semiconductor industry is achieving a bottleneck speed of common devices MOSFET in silicon which can only provide frequency up to Gigahertz (GHz). This limitation creates a high interest of researching on RTD for its application in industry usage.

In order to obtain the ideal result for the fit curve, the physical structure of resonant tunnelling diode have to be optimum in terms of height and thickness. The variation of the physical dimension will affect the I-V performance of RTD device and accordingly affect the result output including the current density and peak to valley current ratio (PVCR)[7]. Significantly, the parameters variation is important in proving the RTD theory and its device operation.

1.3 Objective of Research

This project is aimed:

1. To simulate and obtain the ideal I-V relationship of RTD and prove its device operation theory.
2. To determine the effect of parameters variation including well thickness, spacer thickness, bandgap of the material, barrier thickness and height on the performance of RTD.
3. To model I-V characteristic and fit the curve using physics equations and MATLAB simulation

1.4 Scope of Research

The main scope of the research is focus on the material InGaAs/AlAs and GaAs/AlAs. The corresponding current-voltage relationship and characteristics of the DBRTD device will be modelled. This includes determining the optimum parameters such as peak voltage, peak current density and peak to valley current ratio whereas the physical structures consists of the barrier width, well width and spacer thickness using the empirical method by studying and comparing the modelled result with measured result. The comparison between modelled curves with measured result is used to prove the theory operation of RTD. Next proceed will be determining the device structural parameters.

The focus is on the modelling the I-V characteristics of DBRTD device using physics equation and software simulator MATLAB to prove the theory of resonant tunnelling diode. On the other hand, the hardware construction is also not involved for the scope of research because the simulation and modelling are all based on software progress.

1.5 Thesis Outline

Generally, the thesis consists of a few chapters. Chapter 1 introduces the resonant tunneling diode (RTD) briefly, states the objectives and the scope of the research work. This will give readers an overview of the project.

Chapter 2 covers the literature review which internally shows the detail studies of RTD structures, basic operation with fundamental quantum mechanics theory, characteristics and parameters by numerical analysis and mathematical equations. This chapter presents the background knowledge and applications theory of RTD.

Chapter 3 presents the methodology used for the project. Overviewed flow chart is shown to acknowledge the progress flow of the research. Mathematical equations and empirical method are used to calculate the parameters. Software approach MATLAB is employed for the fitting and modelling the curve to compare with the measured result.

In chapter 4, the expectation and results of the research is presented which includes the I-V curve obtained from MATLAB simulation. The simulation result is used to compare with the measured one and a further discussion is made for the chapter. Physical parameters optimized and determined will also be stated in the chapter.

While in chapter 5, a summary of data with basic arguments is concluded along with the implications of findings. Inferences from study and research are made and discussed. Research questions, objectives and re-statement are finalized and focus on overall significance at the ending.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

In this chapter, we will discuss about the basic operation and theory of RTD which includes the quantum mechanics and the current-voltage (I-V) relationship of RTD devices. In addition, we will study the structures of the RTD to understand the physical details of the device. Next, we will discuss the structural parameters relating to RTD devices and explain the effect of the parameters variation onto the I-V characteristics and performance of the device. Finally we will touch on some RTD applications with its high frequency capability.

2.2 Resonant Tunneling Diode

2.2.1 Intraband Tunnelling

Resonant Tunnelling Diode (RTD) is a device where its electrons tunnel through the barrier at the resonant state. Basically, semiconductor devices have two types of tunnelling mechanism, interband and intraband tunnelling. Interband tunnelling describes the tunnelling electrons occur from conduction band to valence band or tunnelling holes occur from valence band to conduction band [6]. This tunnelling mechanism requires bipolar p-type and n-types doping device. For RTD, it uses intraband tunnelling mechanism which requires unipolar device n-type or p-type doping only. In this mechanism, electrons tunnel from conduction band to conduction band, holes tunnel from valence band to valance band [6].

2.2.2 Quantum Mechanics

Resonant Tunnelling Diode (RTD) operates based on the principle of quantum mechanics where its particles having wave-like properties [4]. The particles are not necessary to have greater or equal energy than the potential barrier to overcome it. In other word, the electrons can pass through the barrier and appear on another side of barrier using tunnelling method with some probability. If the barrier is sufficiently thin compared to the electrons wavelength, the electrons can tunnel through the barrier. On the other hand, for the common classical mechanics which applying on conventional diode, the electrons have to acquire sufficient kinetic energy to overcome the barrier. Consequently, the electrons need to rebound the barriers repeatedly and hence surmount the barrier. Figure 2.1 shows the comparison between classical mechanics and the quantum mechanics tunnelling in RTD [6]. It also seems that the tunnelling behaviour pioneer to thinner barrier. The thinner is the barrier, the higher probability of electrons tunnel through the barrier.

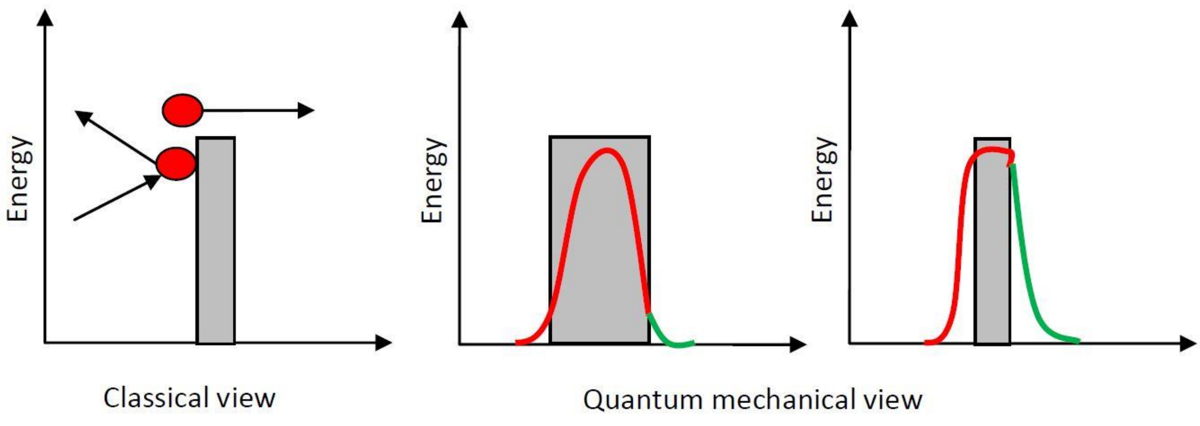


Figure 2.1: Classical mechanics tunnelling vs Quantum mechanics tunneling [6]

2.2.3 Principle Operation

Double Barrier Resonant Tunnelling Diode (DBRTD) basically consist of two barrier layers that allow the electrons flow from emitter to collector. The electrons flow is manipulated by the external diode bias. In Figure 2.2, [6] consider the flow of electrons for the barrier is from left to right. As shown in Figure 2.2(a), zero external bias will cause no current flow as the electrons on barriers sides form a fermi-level above conduction band edge [8]. The electron fermi energy is lower than the quantised energy inside the quantum well. In Figure 2.2(b), an external bias is applying in small amount, the current will start to flow through the diode as in the graph shown point 'b' due to the increased electrons with sufficient energy to overcome the barrier. Consequently, the first resonant state E_1 is lowered in order to match the fermi energy E_f. When the external bias is further increased, the current flow continues to increase. The alignment of electron energy is further adjusted, until the quantised state energy E_1 is equal to the conduction level energy from emitter E_C as in Figure 2.2(c), resonance is occurred. The resonant tunnelling allows more electrons to flow through the barrier until the current flow is maximum where point 'c' the peak voltage and peak current has reached. Off resonance condition occurs when the first resonant energy E_1 is lower than the conduction band offset E_C which happened in Figure 2.2(d). This condition will oppose the nature Ohm's law whereby the increase of voltage will decrease the current. The condition keeps on-going until a new mechanism takes place as in Figure 2.2(e) when the second resonant level E_2 equals to the conduction energy level E_C. This mechanism results the increase of current as the electrons acquired high kinetic energy to overcome the barrier by increasing voltage. As the second resonant energy level E_2 falls below the fermi level E_f, the current flows is increasing back as it is controlled by the mechanism so called thermionic emission over the barrier with the increase of voltage shown in Figure 2.2(f).

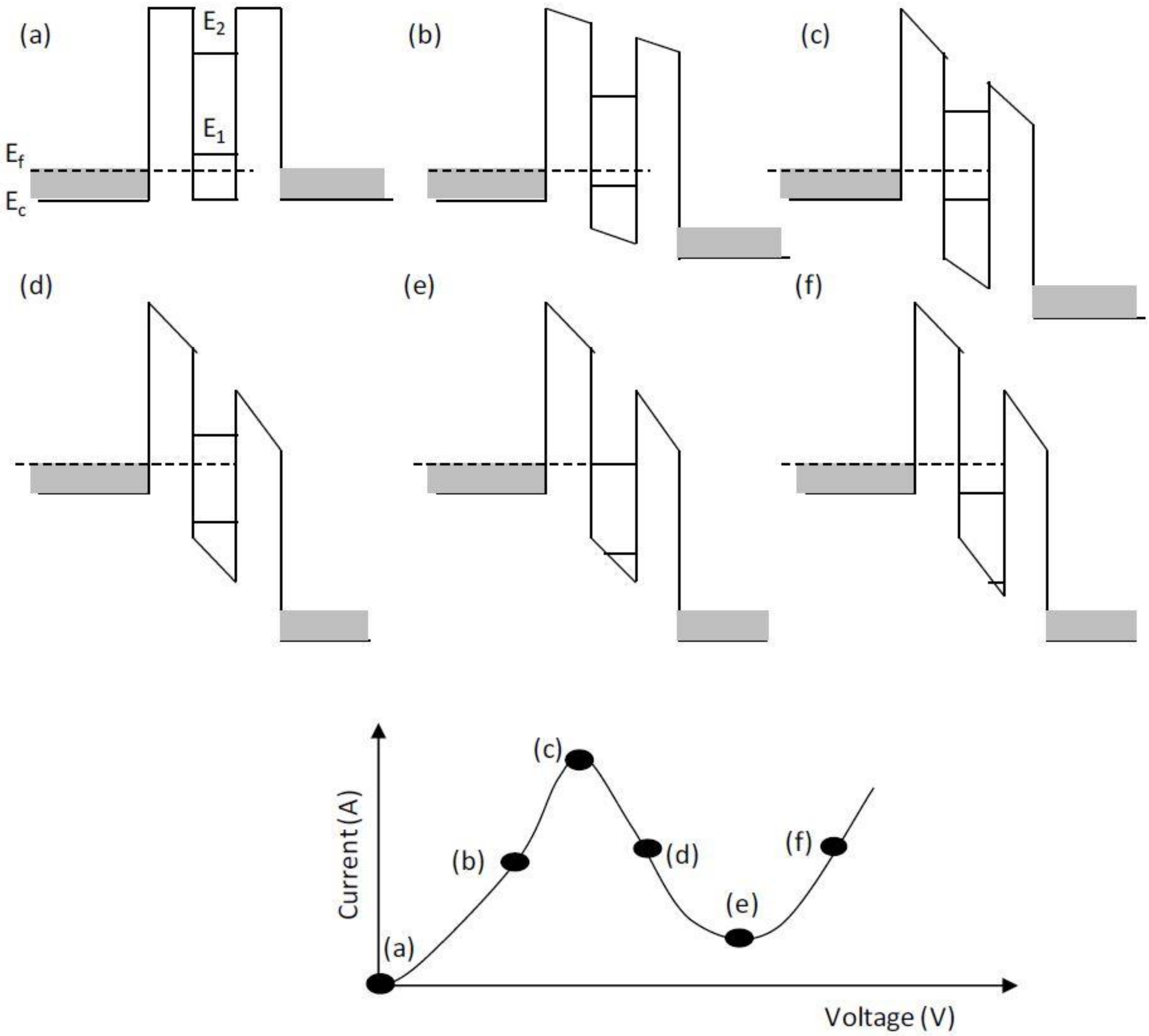
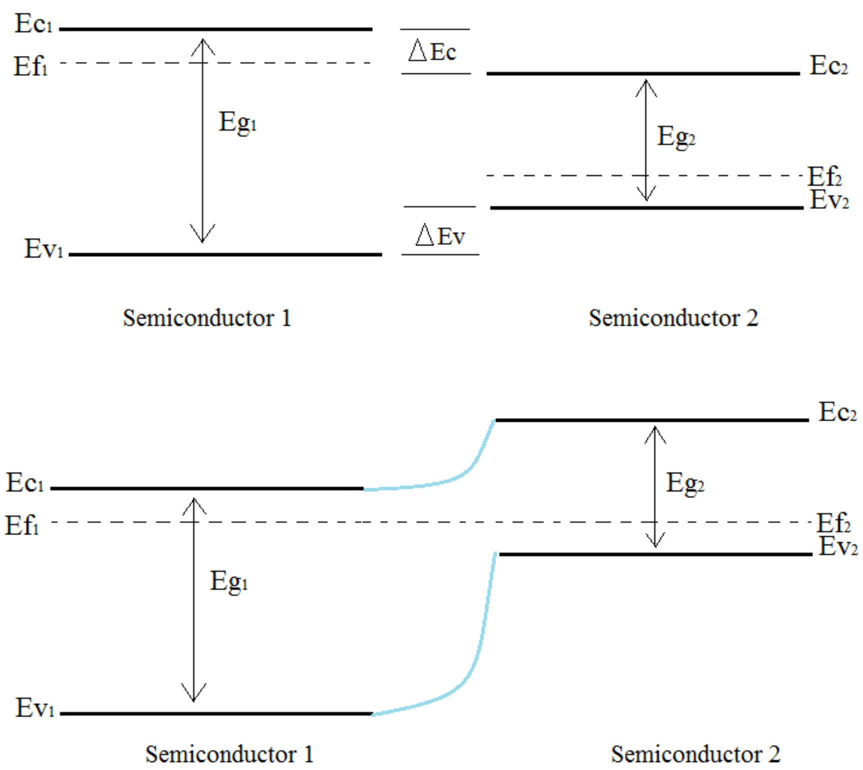


Figure 2.2: Energy band diagram with corresponding I-V Characteristics of RTD [6]

2.3 RTD Structure

2.3.1 Heterostructure

Heterojunction is the interface contact between two different semiconductor materials with dissimilar bandgaps [9]. For instance, AlAs which are group III materials have wide bandgap while group V materials GaAs and InGaAs have narrow bandgap. Heterojunction holds the control of transporting carriers independently. Band discontinuities whereby the conduction and valence band energies changes abruptly determines the electrical property of heterojunction[6]. Resonant Tunnelling Diode (RTD) is a heterostructure which contains more than one heterojunction. Figure 2.3 shows the heterojunction with respective energy band levels.



Where $E_C = Conduction$ Band Energy

$E_C = Fermi\ Energy$

$E_C = Valence\ Band\ Energy$

Figure 2.3: heterojunction with respective energy band level [6]

2.3.2 Lattice Matching

The band discontinuities formed by dissimilar semiconductor materials do not guarantee freedom to RTD designer. A lattice matching material pair with very close lattice constant is needed in order to form a good rated heterojunction interface. It is crucial to minimize the disturbance, if there is any broken bonds [6]. Table 2.1 shows the some semiconductors with their respective lattice constant value and band gap energy [6].

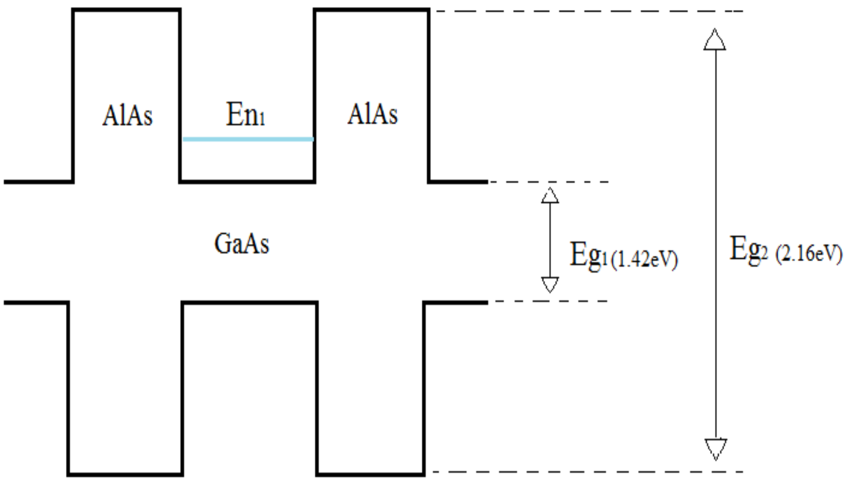
Table 2.1: Lattice constant and band gap energy of III-V group of semiconductors [6]

Alloy	Lattice constant, Å	Band gap energy, eV
GaAs	5.653	1.42
AlAs	5.661	2.16
InP	5.869	1.35
InAs	6.058	0.37
$In_{0.53}Ga_{0.47}As$	5.868	0.76

Mismatching lattices will cause crystalline defects in the form of dislocations which trap electrons or holes, making poor electrical properties of the device. Thus, a lattice-matched system is very important to create a high quality heterojunction.

2.3.3 Quantum Well

A narrow band gap semiconductor layer forms a quantum well when it is sandwiched between two wider band gap semiconductors layers which can be referred as the barrier for the quantum well. The concept can be visualise from the Figure 2.5 and Figure 2.4. AlAs are the wider band gap semiconductors sandwiches GaAs and InGaAs which are the narrow band gap semiconductors.

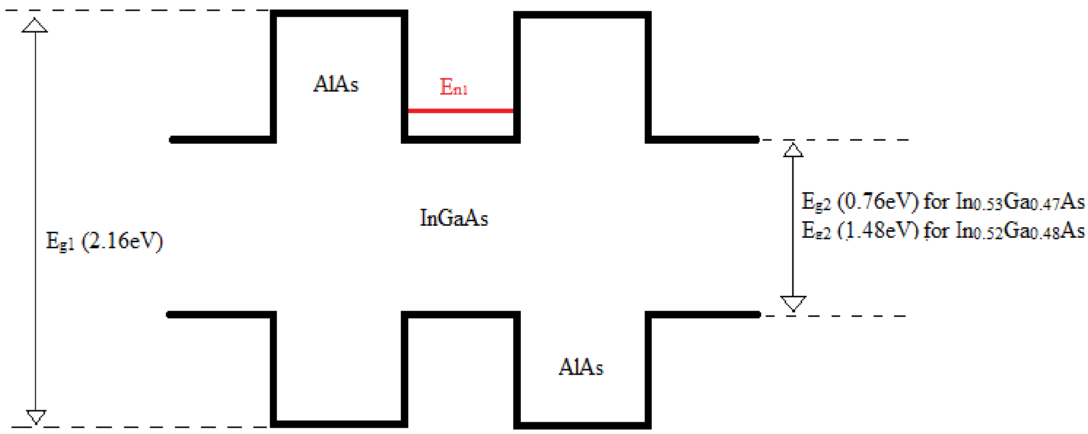


Where $E_{g1} = GaAs\ band\ gap\ energy$

$E_{g2} = AlAs\ band\ gap\ energy$

$E_{n1} = First\ quantization\ energy$

Figure 2.5: Ideal band diagram of GaAs/AlAs DBRTD device [6]



Where $E_{g1} = AlAs\ band\ gap\ energy$

$E_{g2} = InGaAs\ band\ gap\ energy$

$E_{n1} = First\ quantization\ energy$

Figure 2.4: Ideal band diagram of InGaAs/AlAs DBRTD device [6]

2.3.4 RTD: Structural Parameters

In order to obtain a well-performed DBRTD, device quantum well should be made of very close lattice constant semiconductors as mentioned above. The material system used onto the device is essential for the overall performance. This is because the device designer can have the freedom to adjust the barrier heights and band gap of the materials, and also flexibility on mobile electrons and doping concentrations for the contact regions between two dissimilar semiconductors [10]. For this research, the focus will be on two lattice-matched semiconductors products, GaAs/AlAs and InGaAs/AlAs. There are a few physical layer dimensions are able to vary in order to optimise the device performance and capability. Those parameters are barrier thickness (t_b), spacer thickness (t_S), quantum well thickness (t_{qw}).

2.3.5 Barrier Thickness (t_b)

Barrier thickness is one of the important parameter to optimum RTD device performance. In the relation of barrier thickness, it could be referred as the distance for the electron tunnelling from one side to another. The thicker is the barrier, the less electrons allowed to tunnel through the device and hence a lower current density and poor electrical property for the device. At the same context, the carrier transmission probability T (E) is proportional to the barrier thickness. The Equation (2.1) shows the relationship.

$$T \;\boldsymbol{\alpha}\; e^{-2Kt_b} \qquad (2.1)\ [6]$$

Where

$$K = \sqrt{\frac{2m_b V}{\hbar^2}} \qquad (2.2)\ [6]$$

And t_b = Barrier Thickness $\quad h$ = Reduced Planck Constant

V = Potential Barrier $\quad m_b$ = Electron Effective Mass

Usually thinner barrier will give a larger current density exponentially, as the resonant tunnelling current of device depends on the Equation (2.1).

2.3.6 Spacer Thickness (t_S)

Undoped or low-doped spacer is included during the wafer growth to inhibit the diffusion of dopants from doped region to subsequent layer barrier of RTD. The presence of undoped spacer between the emitter and collector will form a triangular well [11] when large bias is applied as shown in Figure 2.6. A sharper resonance will occur in the well region with improved peak-to-valley-current ratio (PVCR) but trade off with lower peak current density. [6]

Therefore, a thicker spacer is able to get a wider depletion region, increase the intrinsic delay time, and overall compromise a higher frequency performance.

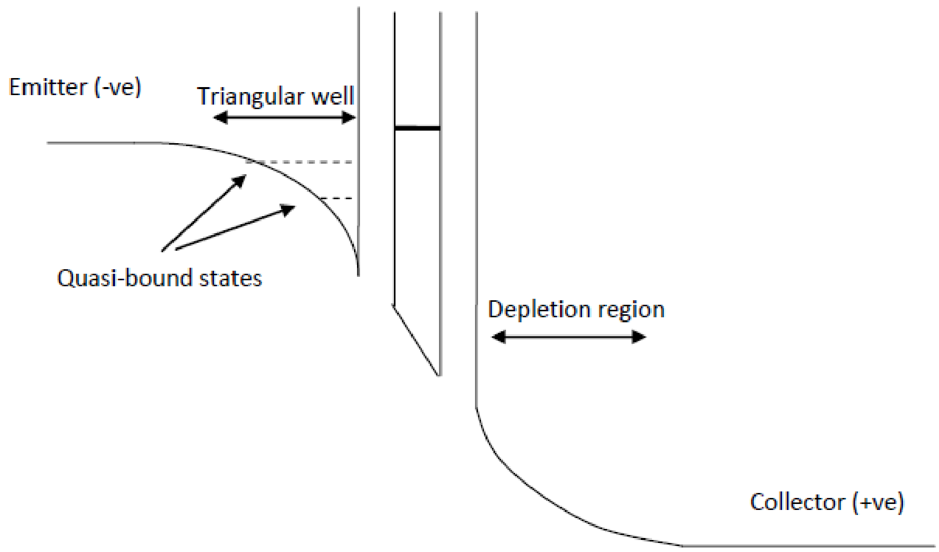


Figure 2.6: Band diagram of RTD with spacer layer [6]

2.3.7 Quantum Well Thickness (t_{qw})

Generally, the quantum well thickness is effective on a few important values for RTD performance. Those are peak voltage, resonant tunnelling current, and peak-to-valley current ratio PVCR. A narrow quantum well is able to boost up the quantization energy inside the well because of the Equation (2.3) mentioned.

Quantization Energy Level, $E_r = \frac{\pi^2 h^2}{3m^* {t_w}^2}$ (2.3) [12]

Where, h = reduced Planck's constant value

m*= electron effective mass

t_w = quantum well thickness

The relationship between quantization energy and quantum well thickness is inversely proportional. The thinner the quantum well thickness, the higher the quantization energy, and thus increasing the peak voltage, PVCR and also the peak current density. In short, narrow quantum well thickness can make a good performance RTD device.

2.4 RTD: IV Characteristics

As mentioned in the principle operation of RTD, the characteristic can be shown by plotting the I-V graph. The graph contains the significant characteristic – the Negative Differential Resistance (NDR) region which does not exist in conventional diode I-V graph. The main key points are the peak current density and peak valley current ratio as shown in Figure 2.7 [13]

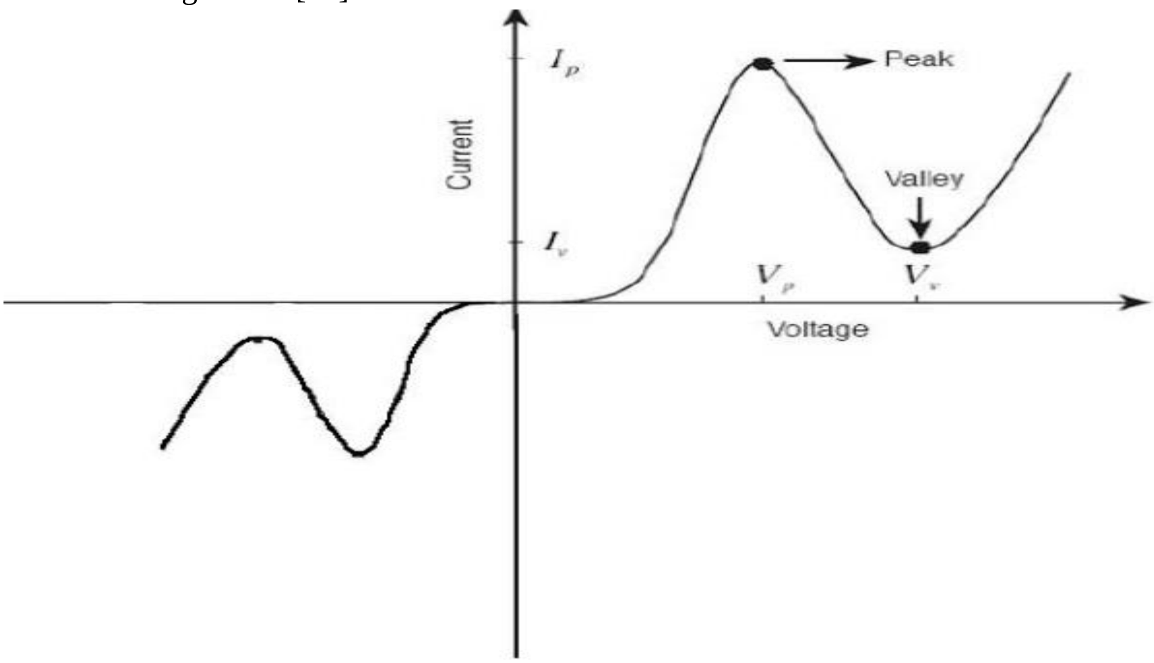


Figure 2.7: Ideal I-V Characteristics of RTDs [13]

Negative Differential Resistance occurs when the electrons tunnel through the barrier in resonance state [14]. It creates a formation of negative resistance region which oppose the Ohm's law whereby the current decreases when voltage increases. This concept was first suggested by Tsu and Esaki in 1973 [1]. The graph shown in Figure 2.7. shows that the NDR starts from the point peak current in resonance state, continues until the valley current point. Therefore, the peak current and the valley current which related to peak valley current ratio (PVCR) is a big criteria for creating NDR.

$$PVCR = \frac{I_p}{I_v} \tag{2.4}$$

From the Equation (2.4), peak current I_p has to be as high as possible whereas valley current I_V has to be as low as possible in order to gain a large value of PVCR and thus creating a larger region of NDR. This is the way to obtain an ideal RTD. The high speed frequency up to THz range is role by NDR as the RTD device has short tunnelling time, very small in size and generates small capacitance.

2.5 RTD: Current-Voltage Equation

Other than the structural parameters, the physical parameters are also important in terms of expressing the I-V characteristic and improving the RTD performance. The physical dimensions are available in the equation for modelling the RTD I-V characteristic as mentioned previously. The total current density of RTD is the summation of current density of normal diode, J_2 and integration current density from zero bias to the end of NDR region, J_1 as shown in Equation (2.5)

$$J = J_1 + J_2 \qquad (2.5)\ [12]$$

Where,

$$J_1 = \frac{em^*kT}{2\pi^2\hbar^3}\int_0^\infty dET(E,V).ln[\frac{1+e^{\frac{E_f-E}{kT}}}{1+e^{\frac{E_r-E-eV}{kT}}}] \qquad (2.6)\ [7]$$

$$J_2(V) = H(e^{\frac{n_2eV}{kT}} - 1) \qquad (2.7)\ [7]$$

And,

$$T(E,V) = \frac{(\frac{\Gamma}{2})^2}{[E-\left(E_r-\frac{eV}{2}\right)]^2+(\frac{\Gamma}{2})^2} \qquad (2.8)\ [7]$$

Where, E = energy measured up from emitter conduction band edge

E_f = Fermi Energy Level

E_r = Resonant Energy

Γ = Resonant Width

$\hbar$ = Reduced Planck Constant

Equation (2.6) is integrated and results in Equation (2.9) and simplified in Equation (2.10) by substitution of parameters A, B, C, D, and n_1. Whereas the substitution parameters are shown in Equations (2.11), (2.12), (2.13), and (2.14).

$$J_1(V) = \frac{em^* kT\Gamma}{4\pi^2\hbar^3} ln\left[\frac{1+e^{\frac{E_f-E_r+\frac{eV}{2}}{kT}}}{1+e^{\frac{E_f-E_r-\frac{eV}{2}}{kT}}}\right].\left[\frac{\pi}{2}+tan^{-1}\left(\frac{E_r-\frac{eV}{2}}{\frac{\Gamma}{2}}\right)\right] \quad (2.9)\ [7]$$

$$J_1(V) = A\, ln\left[\frac{1+e^{(B-C+n_1V)(\frac{e}{kT})}}{1+e^{(B-C-n_1V)(\frac{e}{kT})}}\right].\left[\frac{\pi}{2}+tan^{-1}\left(\frac{C-n_1V}{D}\right)\right] \quad (2.10)\ [7]$$

$$A = \frac{em^* kT\Gamma}{\pi^2\hbar^3} \quad (2.11)\ [12]$$

$$B = \frac{E_f}{e} \quad (2.12)\ [12]$$

$$C = \frac{E_r}{e} \quad (2.13)\ [12]$$

$$D = \frac{\Gamma}{2e} \quad (2.14)\ [12]$$

Where, m^* = Effective mass

2.6 RTD: Application

The capability of RTD generating frequency up to THz and its special characteristic NDR make it applicable to be an oscillator. RTD device is able to bias into negative differential region, cancelling the circuit resistance and obtain an oscillation with high speed performance up to THz. A sample circuit diagram and the simulation result is shown in Figure 2.8. Digital circuit such as frequency multiplier also applicable for RTD device [8]. It potentially increases the processing speed and reduce the time processed, and therefore improving the device efficiency. Figure 2.9 shows the circuit diagram and simulation result of frequency multiplier.

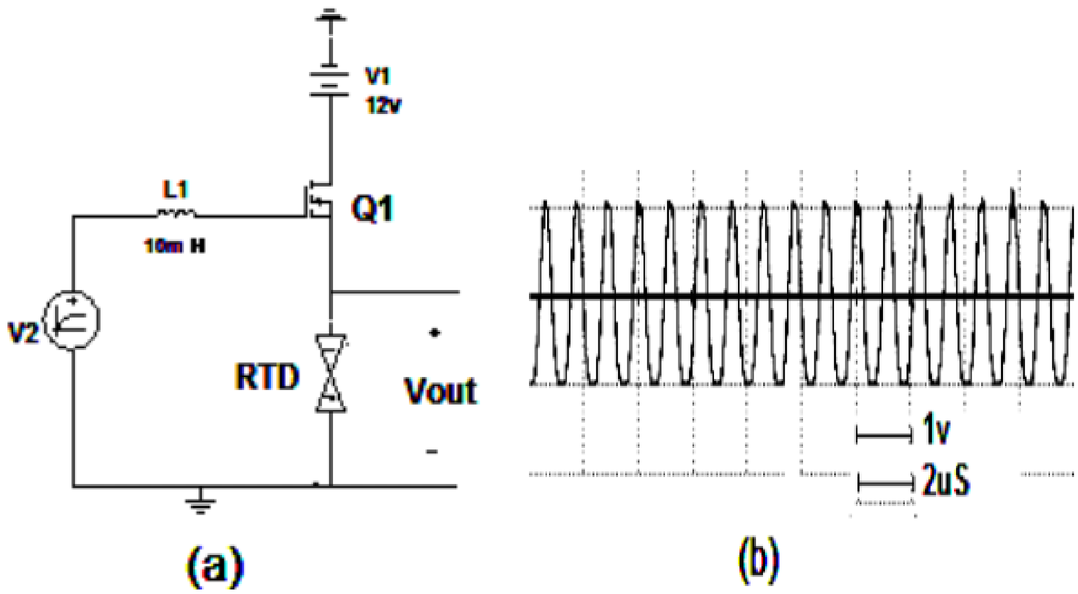


Figure 2.9: RTD device oscillator (a) Circuit diagram (b) Simulation result

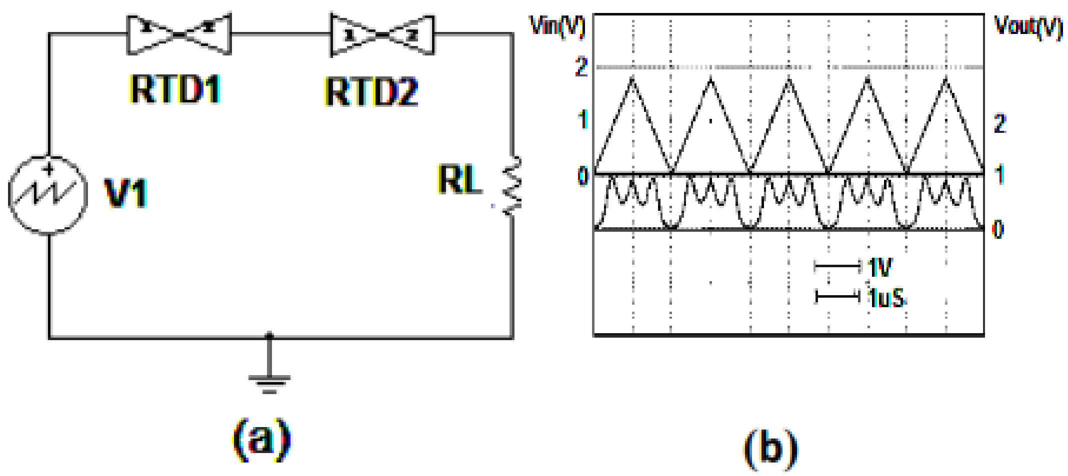


Figure 2.8: RTD device frequency multiplier (a) Circuit diagram (b) Simulation result

CHAPTER 3: METHODOLOGY

For this chapter, a brief methodology on modelling the current-voltage (I-V) relationship of two resonant tunnelling diodes (RTD) structures will be discussed. The structures are GaAs/AlAs and InGaAs/AlAs double barrier resonant tunnelling diode (DBRTD). Mainly the empirical simulation focus will be using MATLAB as the simulator tool to present the I-V Characteristic or curve of the device. From the graph simulated, a few important parameters (A, B, C, D, H, n_1, n_2) will be obtained using reverse engineering process through the curve fitting. For the following session we will discuss the process details with presentable diagrams, flow charts, tables and equations.

3.1 Empirical modelling

Empirical method is an experiment-based research for theory verification [6]. As mentioned above, the modelling main focus is to obtain an I-V curve with best fit as in Figure 2.7 comparing to the measured result [Appendices C & G] provided to research on the diode characteristics and the device performance. Besides, RTD structural parameters and unknown parameters as mentioned in Equation (2.10) are to be obtained as well as the simulation has to be working together with the Equations (2.5) and (2.7). Using empirical method, the parameters have to be determined at first by reverse engineering process and calculation. Reverse engineering refers to finding the solution using the trial results and improving by repeating the method experimentally. A comparison of performances and the data received will be made between two RTD structures, GaAs/AlAs and InGaAs/AlAs devices after modelling done.

3.2 Unknown & Fitting Parameters

Parameters A, B, C, D are dependent parameters for RTD. Every single parameter is the factor affecting the current and voltage of the modelling devices. These parameters will be used to determine the shape of curve and I-V characteristics and also the structural parameters such as quantum well thickness(t_{qw}) and barrier thickness(t_b). The unknown parameters can be obtained from MATLAB simulation with reverse engineering process repeatedly until the best fit curve is formed by using the equation mentioned above in section 3.1 with current density Equations (2.5), (2.7) and (2.10).

Meanwhile fitting parameters H, n_1, n_2 are helpful in forming the shape of curve associating the unknown parameters in modelling. The unknown parameters A, B, C, and D are only estimated values which will not drive the optimum performance simulated initially. We can only obtain a close ideal I-V curve fitting by varying and simulating empirically with adjusted parameters (A, B, C, D, n_1, n_2, H). From time to time, we need to observe the graph shape and analyse the curve with important points such as peak current and voltage and peak valley current and voltage in the NDR region. These parameters are still to be adjusted based on the curve, and depends on the structural parameters at the same time.

In addition, an alteration of around 10 % positively and negatively will be made for the parameters in order to investigate and study the effect of alteration of parameters onto the I-V curve in term of peak and valley points.

A flow chart of the overall process of obtaining I-V curve is presented in Figure 3.1.

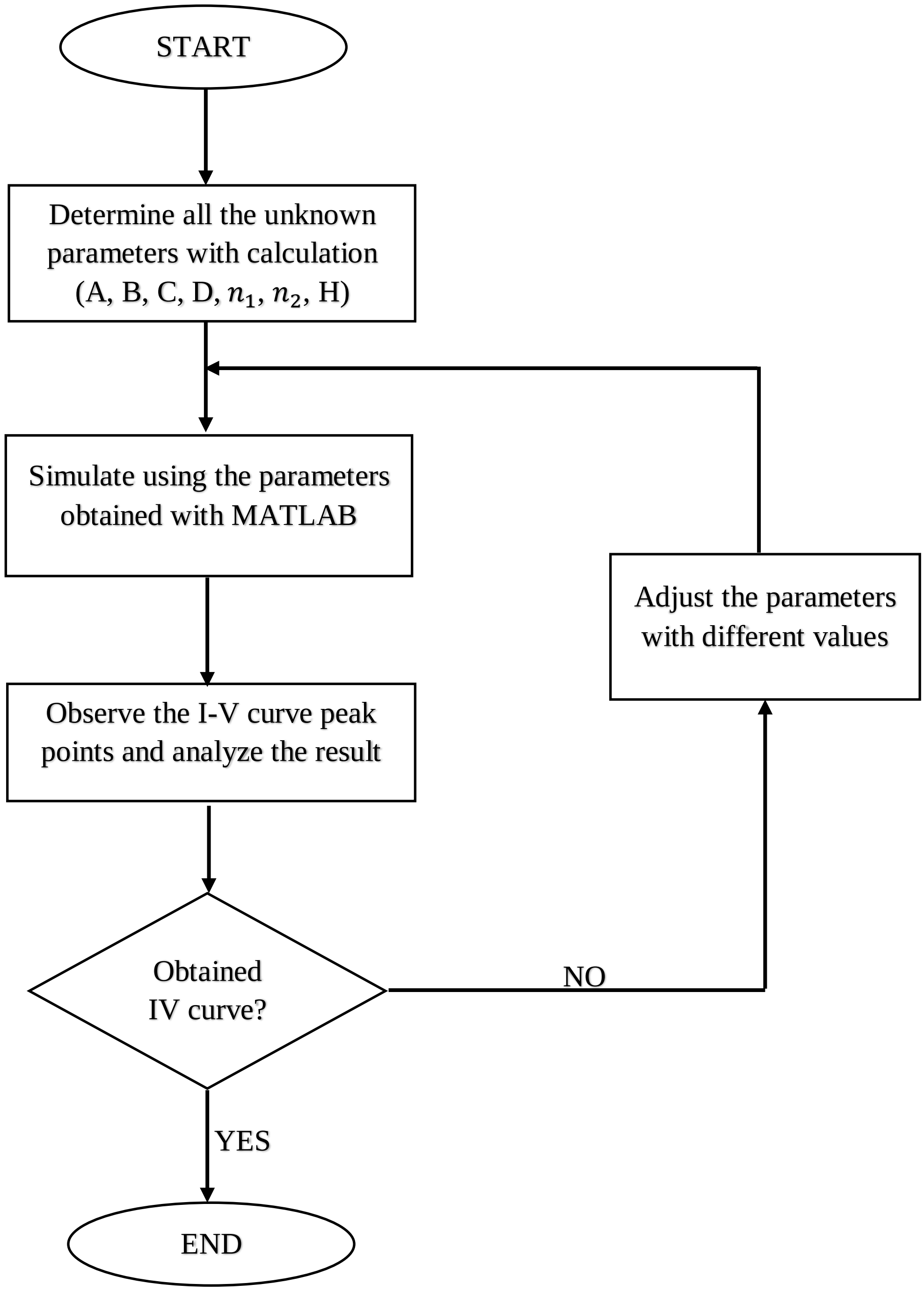


Figure 3.1: Process flow of simulating the I-V curve using parameters variation

3.3 Structural Parameters

Reverse engineering process is utilised for determining the structural parameters from the unknown parameters. These values can be calculated after comparison of simulated curve with measured I-V curve. The process fitting through comparison is shown on flow chart in Figure 3.2 in next page. The values should be in an acceptable range of 10 % or lesser compared with measured result. This is because structural parameters are considered optimized and RTD can run good performance with variation within 10 % [15]. To achieve optimization of device structural parameters, unknown parameters still need to be varied continuously with the curve fitting using MATLAB application. The percentage difference between two data can be calculated as the Equation (3.6).

$$Percentage\ Difference\ (\%) = \frac{Simulated\ data - Measured\ data}{Measured\ data}\ x\ 100\% \qquad (3.6)$$

The real findings of device structural parameters can be obtained from the various equations and substitutions. The related particulars in the equations can be calculated using Equations from (3.1) to (3.5). While these equations require substitution of unknown parameters from the equations from (2.11) to (2.14).

For quantum well thickness, parameter C is used for substitution of resonance energy in Equation (3.5) and (2.13), ideal effective mass of GaAs and InGaAs are taken for the value of 0.067 m_0 and 0.041 m_0 in resonance energy substitution respectively.

For barrier thickness, Equation (3.2), (3.3), (3.4) and (2.14) are used. Also in the substitution, the energy bandgap in Equation (3.4) used is 1.08 eV where AlAs energy band 2.16 eV divided by two, ideal effective mass as well as parameter C and D are also included.

While for the effective mass simulated value, the Equations involved are (2.11) and (2.14) which requires parameter A and D.

$$E_f = E_C - KT\,ln\frac{N_C}{N_d} \qquad (3.1)\ [12]$$

$$\Gamma = 4\,E_r e^{2k_R t_b}(kt_w + 2\frac{k_r}{k_R})^{-1} \qquad (3.2)\ [12]$$

$$k_r = \frac{\sqrt{2m^* E_r}}{\hbar} \qquad (3.3)\ [12]$$

$$k_R = \frac{\sqrt{2m^*(\phi - E_r)}}{\hbar} \qquad (3.4)\ [12]$$

$$E_r = \frac{\pi^2 h^2}{3m^* {t_w}^2} \qquad (3.5)\ [12]$$

As mentioned above, the optimization of the structural parameters must be achieved at the same time fitting the curve in the modelling process. The process shall be repeated empirically as shown in the flow charts in Figure 3.1 and Figure 3.2. Therefore, various adjustments, experiments, and empirical modelling need to be carried out repeatedly until a best curve fit with optimized device parameters has achieved in order to do a good modelling. A flow chart of the overall process of optimizing structural parameters and fitting I-V curve is presented in Figure 3.2.