ANALOG STRUCTURAL MODELING OF RESONANT TUNNELING DIODE USING LTSPICE

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by

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Thesis submitted in partial fulfillment of the requirements for the degree of Bachelor of Engineering (Electronic Engineering)

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List of Abbreviations

ADCs	Analog-to-digital converters
Al	Aluminium
AlAs	Aluminium Arsenide
AlGaAs	Aluminium Gallium Arsenide
AlSb	Aluminium Antimonide
As	Arsenide
CMOS	Complementary Metal Oxide Semiconductor
DBQW	Double Barrier Quantum Well
DBRTD	Double Barrier Resonant Tunneling Diode
Ga	Gallium
GaAs	Gallium Arsenide
GHz	Gigahertz
InAlAs	Indium Aluminium Arsenide
InAs	Indium Arsenide
InGaAs	Indium Gallium Arsenide
InP	Indium Phosphide
IV	Current-Voltage
MBE	Molecular Beam Epitaxy

NDR	Negative Differential Resistance
PVCR	Peak to Valley Current Ratio
RTD	Resonant Tunneling Diode
THz	Terahertz

Abstrak

Dalam kajian ini, bahan InGaAs/AlAs dan GaAs/AlAs digunakan sebagai bahan untuk DBRTD. RTD adalah peranti elektronik yang paling cepat pada masa kini. RTD terdiri daripada dingding kuantum yang diapit di antara dua halangan nipis InGaAs/AlAs dan GaAs/AlAs. Kedua-dua hujung ditamatkan dengan dopan semikonduktor yang tinggi untuk mewujudkan saluran elktrik. Operasi RTD secara fizikal memerlukan masa pengiraan yang terlalu lama. Dalam rekaan bentuk litar, model ini boleh digambarkan dengan berkesan dalam pemodelan struktur analog menggunakan LTspice. Salah satu cara untuk menghasilkan model yang terbina didalam RTD adalah dengan menggunakan kaedah jadual carian dalam sumber semasa kawalan voltan. Dalam rekaan litar RTD, nilai parameter peranti telah dikira dan simulasi untuk mendapatkan lengkung IV. Lengkung IV telah disimulasi untuk disamakan dengan lengkungan yang dimodelkan dan diukur dari kajian yang terdahulu dari Zawai et. al [3] pada 2015 untuk mengekstrak parameter struktur peranti. Kajian simulasi peranti pada perwakilan litar adalah penting juga untuk membawa RTD dalam aplikasi sebenar yang merupakan salah satu objektif kajian. Simulasi rekaan litar menggunakan RTD model yang direka di dalam kajian ini merupakan satu kejayaan dalam membuktikan teori peranti RTD menunjukkan bahawa, bahan-bahan yang berbeza RTD akan menghasilkan keluaran PVCR yang berbeza dan membuktikan teori RTD dengan baik.

Abstract

In this research, the material InGaAs/AlAs and GaAs/AlAs are used as the material for the double barriers resonant tunneling diode (RTD). RTD is the fastest electronic device to date. RTD consists of a quantum well sandwiched in between two thin barriers InGaAs/AlAs and GaAs/AlAs. Both ends are terminated with a highly doped semiconductor to provide electrical contacts. The operation of RTD physical model requires extremely long calculation time. For circuit design, this model can effectively be described in analog structural modeling using LTspice. One of the ways to implement the built-in model for an RTD is by using lookup table method in the voltage controlled current source. In the circuit representative of RTD, the value of device parameter had been calculated and simulated to get the IV curve. IV curve had been simulated to match the modeled and measured curve which obtained from the previous work by Zawawi et. al [3] in 2015 to extract the structural parameters of the device. The study on device simulation on the circuit representation was important as well in order to bring RTD in real applications which is one of the objectives of the work. The simulation of circuit applying the purposed RTD model in this work was a success in proving the theory of RTD device shows that, different materials of RTD will produce a different peak to valley current ratio (PVCR) while correspond well with the theory of RTD device.

CHAPTER 1 Introduction

1.1 Research Background

It is well documented that today's advanced information technology is mainly attributed to the electronic representation and processing of information in a low-cost, high-speed, very compact, and highly reliable fashion, and that the quest and accomplishments of continual miniaturization and integration of solid-state electronics have been the key to the success of the computer industry and computer applications [1]. In the future, advanced multimedia infrastructure and services will demand further reduction in chip size. According to Moore's law state, chip density has roughly doubled every other year over the last three decades. For the speed concern in the design and development of integrated circuit, RTD has been shown to achieve a maximum frequency up to Terahertz (THz) as opposed to Gigahertz (GHz) in conventional Complementary Metal Oxide Semiconductor (CMOS) transistor.

Resonant tunneling diode (RTD) is a diode with a resonant tunneling structure in which electrons can tunnel some resonant states at certain energy levels. RTD has been widely studied because of its importance in the field of nanoelectronic science and technology and its potential applications in very high speed/functionality devices and circuits [1]. This device consists of a quantum well sandwiched in between two thin barriers. Both ends are terminated with a highly-doped semiconductor to provide electrical contacts. They have been used in many types of application circuits such as amplifiers, oscillators, pulse generators, and analog-to-digital converters (ADCs) to improve the device frequency.

In comparison to the conventional diode, RTD applies the principle of quantum mechanics instead of classical physics. The principle of quantum mechanics states that the particle has a wave-like property where the particle can pass through the barrier by using tunneling method even it has energy which is less than the barrier height. Before it can pass through the barrier, the particles of the conventional diode need to gain enough kinetic energy compared to the potential energy of the barrier.

In this research, models are to be developed for RTDs that used two types of III-V compound semiconductor which are Indium Gallium Arsenide / Aluminium Arsenide (InGaAs/AlAs) and Gallium Arsenide / Aluminium Arsenide (GaAs/AlAs). Semiconductor InGaAs or GaAs quantum well sandwiched between the two layers of barriers of AlAs as the barrier. The differences in the bandgap energy of both elements are being engineered and combined so that the quantum well consists of the material with lower bandgap energy while the barriers consist of the material with higher bandgap energy. The corresponding current-voltage relationship of the device will be observed and compared with the measurement result.

1.2 Problem Statement

RTD is a device which is able to produce frequency up to the THz range. In the current semiconductor industry, the technology can only yield the high-speed device such as MOSFET, which will only provide frequency up to the frequency of GHz [2]. In previous studies, an experiment was carried out to obtain the IV characteristics of the RTD device. However, these situations have created the opportunity for continuing researches on RTD for its application in the electronic application.

There various methods that can be used to implement a suitable RTD method. In this thesis, three different methods are mentioned. However, some of this method require extremely long calculation time. In this work, the RTD model is effectively described in analog structural modeling using LTspice for the circuit design. They are all based on the experimental I-V characteristics of the RTD and its large signal equivalent circuit. The LTspice before this does not include a built-in model for an RTD.

1.3 Objectives of Research

The objectives of this project are as follows:

i. To investigate the LTspice compatible model for resonant tunneling diode of InGaAs/AlAs and GaAs/AlAs by using table function.
ii. To compare the IV characteristics obtained from the simulation results against the measured result.
iii. To develop a test circuit for the resonant tunneling diode model.

1.4 Scope of the Research

The main focus of this project is mainly on the InGaAs/AlAs and GaAs/AlAs RTD device. The IV relationship of this RTD device will be determined. Throughout the project, the fabrication of InGaAs/AlAs and GaAs/AlAs RTD will not be carried out. Device structural parameters such as the effective mass, barrier thickness, and quantum well thickness will be based on the given data sheet. The current-voltage characteristics like the peak current density, peak voltage as well as the peak to valley current ratio will be obtained based on the experimental values. The parameters obtained will be simulated using LTspice. The final results will be used to compare with the measured value. The results should be within the acceptable range. A library file for the large and small signal representation of the RTD will be created for the future development of this device.

1.5 Thesis Outline

In Chapter 1, a brief introduction about this project is stated. This includes the background of the project, problem statement, research objectives, scope of the research and the thesis outline. In this chapter, it will give the readers an overview of the project.

Chapter 2 focuses on the literature review of the project. The details of the RTD such as the structure, basic operation, characteristics and the parameters of the RTD are discussed in this chapter. This chapter intends to discuss the details about RTD which include the fundamental theory.

Chapter 3 discuss the methodology of the research. The workflow of this research is shown in this chapter via flow charts and detailed explanation is given on them.

Chapter 4 the results of the research were presented in the simulation to model the RTD using LTspice. The results obtained are compared with the measured values. The RTD model was tested in the circuit application. A discussion is made in this chapter to justify the difference between the material used.

Chapter 5 details out the conclusion and future works respectively. This chapter includes the judgment for the results obtained in this research.

CHAPTER 2 Literature Review

This chapter will cover few important aspects which are related to the work on InGaAs/AlAs and GaAs/AlAs double barrier resonant tunneling diode. First of all, the basic operation and concept of RTD device which includes all the theory related such as quantum mechanics, and the relationship between current and voltage of RTD device will be covered. Next, the structure of RTD and the simple fundamental knowledge on the concept of heterostructure are discussed. Thirdly, the material, DC characteristic, and structural parameter of RTD are explained. Finally, some applications in electronic circuits and the performance obtained from the device are mentioned.

2.1 Basic Operation and Concept of RTD

RTD is a quantum well structure semiconductor device that uses electron tunneling and has the unique property of negative differential resistance in its current-voltage characteristics. RTD is based on the principle of quantum mechanics where the particles have the wave-like properties and are moving in wave patterns. In classical physics, a particle can only overcome a potential barrier when the kinetic energy of the particle is greater than the barrier height. However, in quantum mechanics, the particle with incident energy less than the barrier height can tunnel through the barrier and appears on the other side of the barrier with certain probabilities, given that the barrier is thin enough and finite.

In classical physics, an electron must have adequate energy to overcome a barrier. In If the electron does not have adequate energy, the electron will rebind from the barrier as shown in Figure 2.1 (a) to overcome the barrier. Quantum mechanics grant a probability for the electron being on the other side of the barrier. The electron may look larger compared to the thickness of the barrier if treated as a wave. There is still a small probability that will appear on the other side of a thick barrier as shown in Figure 2.1 (b) even if the electron treated as a wave. Thinning the barrier increases the probability that the electron is found on the other side of the barrier.

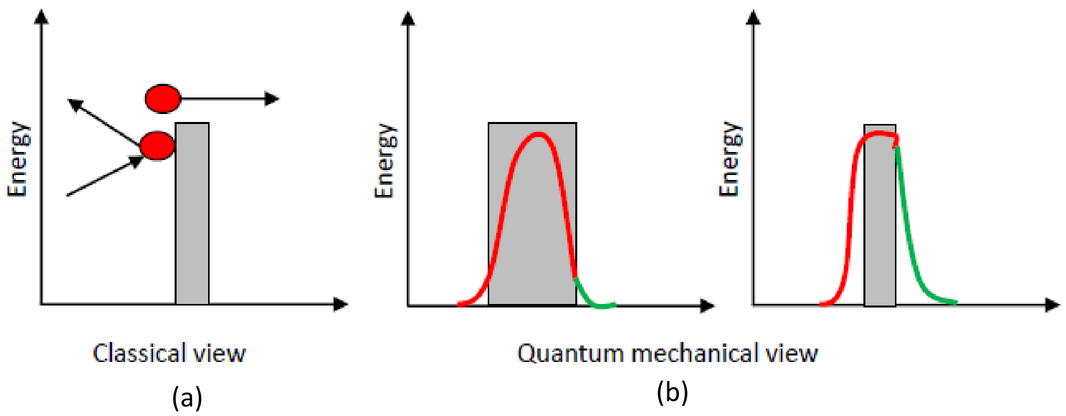

Figure 2.1 Electron particle-wave duality (quantum tunneling) in (a) classical view and (b) quantum mechanical view [3].

Electrons tunnel through a well sandwiched between two barrier layers in following from emitter to collector. The external diode bias, V control the flow of electrons. The typical conduction band diagram of an RTD and the corresponding IV characteristics with respect to applied bias is illustrated in Figure 2.2, where E_c, E_f, E_1, and E_2 are the conduction band, Fermi and quantization energies respectively. Under zero external bias ss in Figure 2.2 (a), the electrons on both sides of the barriers from a Fermi sea of electrons above the conduction band edge due to the high doping concentration of the electrodes. There is no current flow in this condition. The quantised energy states inside the quantum well are greater than the electron Fermi energy.

When there is small applied external bias as in Figure 2.2 (b), the number of electrons with sufficient energy to overcome the barrier increases. A small amount of current starts to flow through the diode when the first resonant state is lowered to match the Fermi energy. As the bias voltage increase further as shown in Figure 2.2 (c), the alignment of the electron energy match quantised state energy, E_1. A resonance occurs when the energy levels are equal, allowing more electrons to flow through the barriers resulting in a peak current. The voltage, at which current flow is maximum, is called the peak voltage.

When the voltage increase, the current drops ideally to zero due to the off-resonance condition as seen in Figure 2.2 (d). As the voltage increased further, the current will keep dropping until other mechanisms take place as shown in Figure 2.2 (e). Current flow is enhanced through the second resonant condition when the second resonant level drops below the Fermi level. At this point, with an increase in voltage, current flow is determined mainly by thermionic emission over the barrier as depicted in Figure 2.2 (f) [3].

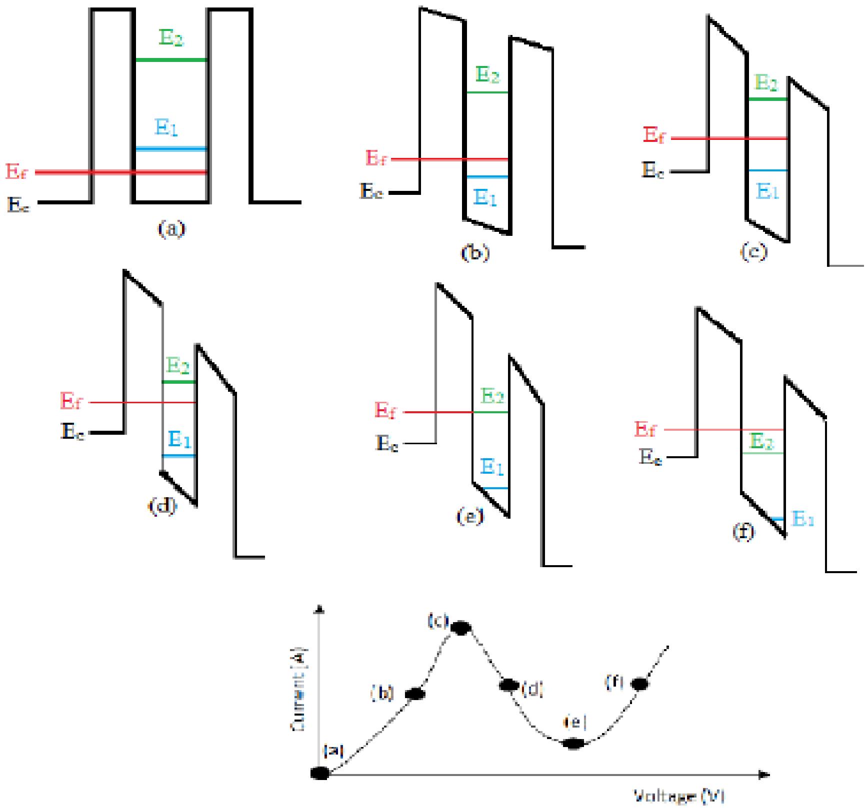

Figure 2.2 Typical energy band diagram of an RTD and the corresponding IV characteristics [3]. (Where Ec, Ef, E1, and E2 are the conduction band, Fermi and quantization energies respectively)

2.2 Structures of RTD

The basic RTD device configuration and the most common RTD structures as described by Sun et al [1] are relevant to this project. This DBQW RTD was first experimentally demonstrated by Chang et al [4]. RTD consists of an undoped quantum well sandwiched between two undoped layers of barriers. The basic structure and most popular materials of RTD are from III-V compound semiconductors. The use of these materials is due to the ability to engineer the band gaps of these materials in order to improve electron mobility, hence higher current density capability.

Figure 2.3 shows the example of DBQW with InGaAs sandwiched between AlAs. In this example, InGaAs is the material and the two layers of Alas are the barriers. The contact region in the example is Ti/Au. However, there are some other material systems being used for producing RTDs with improvements on the DC characteristics namely the peak current density, peak voltage, peak to valley current ratio (PVCR) and negative differential resistance (NDR) [3].

Different material systems will produce different band-gap in RTD device. Thus, it will also affect the performance of RTD device due to high speed and complexity performance. The aim in RTD material system was to produce THz RTD application circuit with the special quantum well structure and the highest peak current density.

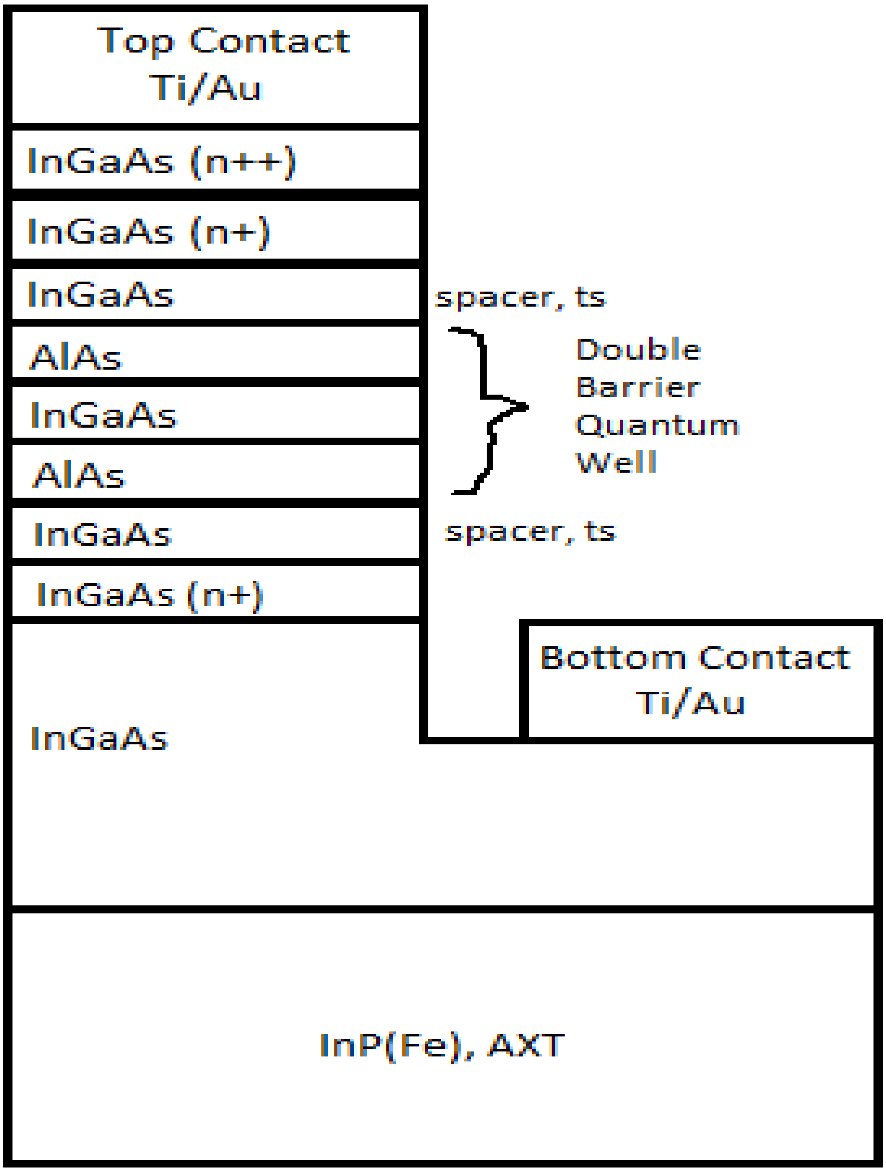

Figure 2.3 Example epilayer structure of RTD using InGaAs/AlAs material system studied in this project [3].

The work presented in this research is one of a few reported molecular beam epitaxy (MBE) grown of indium-rich quantum well structures. Table 2.1 and Table 2.2 below demonstrate the variety of RTD structures grown and characterized in this work [3].

Table 2.1 Sample XMBE230 InGaAs/AlAs RTD grew by MBE [3]

XMBE230			
Layer	**Material**	**Doping (cm^{-3})**	**Thickness (Å)**
Collector 1	$In_{0.53}Ga_{0.47}As$ (n++)	2×10^{19}	450
Collector 2	$In_{0.53}Ga_{0.47}As$ (n+)	3×10^{18}	250
Spacer	$In_{0.53}Ga_{0.47}As$	undoped	200
Barrier	AlAs	undoped	12
Quantum Well	$In_{0.8}Ga_{0.2}As$	undoped	45
Barrier	AlAs	undoped	12
Spacer	$In_{0.53}Ga_{0.47}As$	undoped	45
Emitter 2	$In_{0.53}Ga_{0.47}As$ (n+)	3×10^{18}	250
Emitter 1	$In_{0.53}Ga_{0.47}As$ (n+)	1×10^{19}	4000
Substrate	InP		

Table 2.2 Sample XMBE66 GaAs/AlAs RTD grew by MBE [3]

XMBE66

Layer	**Material**	**Doping (cm^{-3})**	**Thickness (Å)**
Collector	GaAs(n++)	7.0×10^{18}	5000
Spacer	GaAs	undoped	150
Barrier	AlAs	undoped	17
Quantum Well	GaAs	undoped	65
Barrier	AlAs	undoped	17
Spacer	GaAs	undoped	350
Emitter	GaAs(n++)	3.0×10^{18}	8000
Buffer	GaAs	undoped	1320
Substrate	GaAs		

2.2.1 Heterostructures and Heterojunction

The heterojunction is the key recipe in enabling the most advanced semiconductor devices currently being developed and manufactured [5]. In contrast to homojunction, the heterojunction's ability to control the hole and electron carrier transport independently is the reason behind the successful implementation of these devices for high-speed high-frequency applications, optical sources, and detectors [6]. Heterostructures referred when the devices containing more than one heterojunction.

In this research, the heterojunction is the interface formed when two different semiconductor materials from group III-V which is InGaAs/AlAs and GaAs/AlAs has different bandgap come into contact. There are unforeseen changes in both the conduction and valence band energies at the heterointerface. The resulting band discontinuities will then determine the electrical and optical properties of the heterojunction [3]. Figure 2.4 represent the notation used to describe the energy band discontinuities when two materials with different energy band gaps are brought together and thermal equilibrium is established.

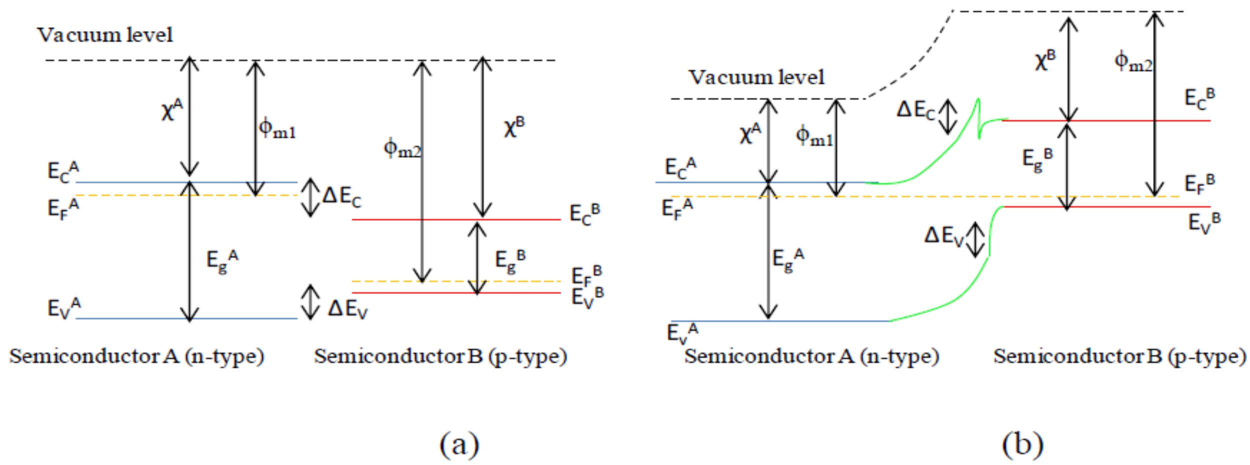

Figure 2.4 Energy band diagrams of two semiconductors materials Figure 2.4 (a) in isolation and Figure 2.4 (b) in contact. Ec is the conduction band energy, Ev is the valence band energy, Ef is the Fermi energy and ϰ is the electron affinities [3].

2.2.2 Lattice Constant

A lattice constant is important and desirable to ensure minimized material dislocation for high performance. Heterojunction indicates that the structure contained more than one semiconductor material with different properties and characteristics, the difference is in term of bandgap energy or lattice constant. Choosing the material pair that has a very close lattice constants is essential to minimize the disturbance at the heterojunction interface caused by broken bonds [3]. In other words, the closer the Lattice constant of the two materials, the better the heterojunction formed. In this research, InGaAs/AlAs and GaAs/AlAs RTD are being chosen to form the heterojunction composed of barriers and quantum well. InGaAs/AlAs RTD have the wider lattice constant of the two materials as compared to GaAs/AlAs RTD. Table 2.3 shows some of the semiconductors together with lattice constant value and band gap energy, E_g.

Table 2.3 Lattice constant and band gap of common III-V binary and ternary compound semiconductors [7]

Alloy	**Lattice constant, a_0 (A)**	**Band gap, E_g (eV)**
GaAs	5.653	1.42
AlAs	5.661	2.16
InAs	6.058	0.37
InP	5.869	1.35
$Al_{0.52}Ga_{0.48}As$	5.657	2.072
$In_{0.53}Ga_{0.47}As$	5.868	0.76
$In_{0.52}Al_{0.48}As$	5.852	1.48

2.2.3 Quantum Well

A quantum well will form when a layer of narrow band gap semiconductor is sandwiched between two thin layers of wide bandgap semiconductor [3]. In this research, the GaAs layer (well) is sandwiched between two AlAs alloy semiconductor (barriers) as shown in Figure 2.5, and InGaAs layer (well) is sandwiched between two AlAs layers (barriers) as shown in Figure 2.6. The electrons and holes in the quantum well unable to move freely in the crystal growth direction (confinement direction), but able to move freely in the plane perpendicular to the growth direction.

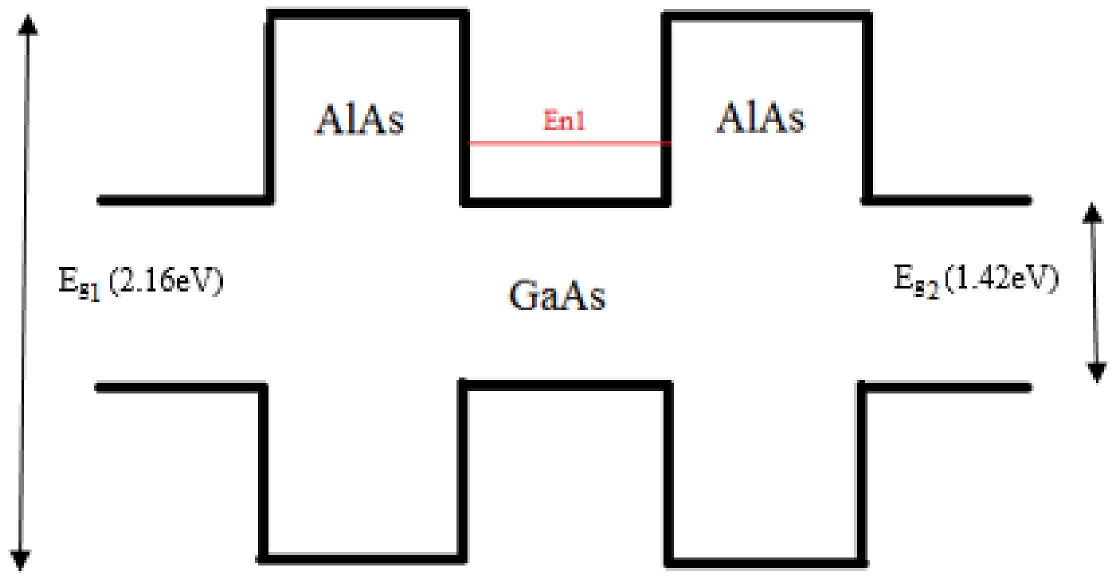

Figure 2.5 Conceptual band diagram of an 'ideal' quantum well formed by a narrow band gap semiconductor (GaAs) sandwiched between two barriers of wide band gap semiconductor (AlAs)

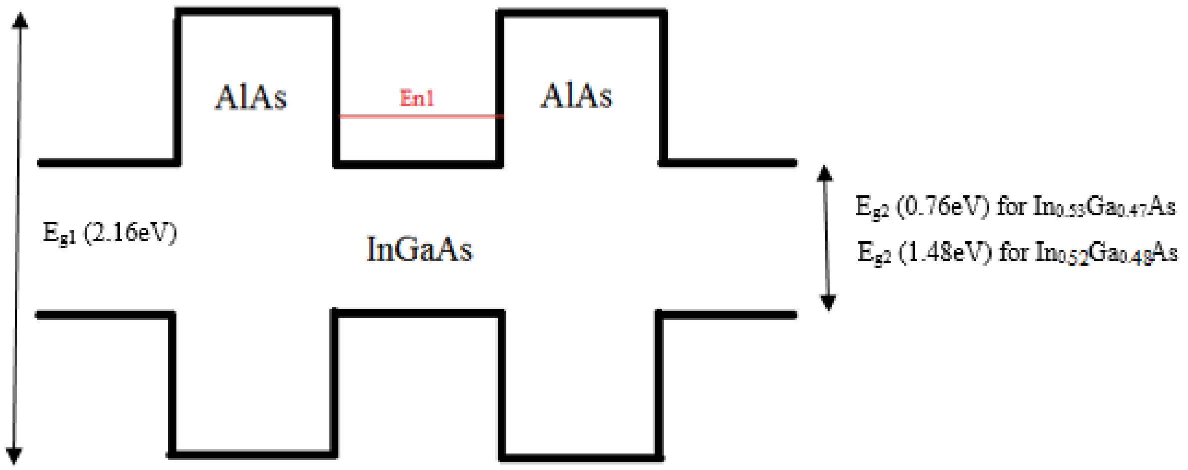

Figure 2.6 Conceptual band diagram of an 'ideal' quantum well formed by a narrow band gap semiconductor (InGaAs) sandwiched between two barriers of wide band gap semiconductor (AlAs)

2.3 Materials of RTD

The most useful RTD material system with increasing peak to valley current ratios (PVCR) respectively which can be used to fabricate RTD such as GaAs/AlGaAs, GaAs/AlAs, InGaAs/InAlAs, InGaAs/InAlAs, InGaAs/AlAs and InAs/AlSb. However, the material system used in this research in InGaAs/AlAs and GaAs/AlAs which is the wider PVCR being compared with the smallest PVCR.

RTD with GaAs/AlAs material system had been introduced for the first time by Tsuchiya et.al [8] in 1985. The electrodes were highly doped and NDR at room temperature was observed. The improvement in peak to valley current ratio (PVCR) was attributed to less alloy scattering in AlAs barrier lead to a reduction in leakage current components and also less leakage through higher resonant level due to increased barrier height. In this work, conventional GaAs/AlAs RTD epilayer structure, DC characteristics, and comparison with other work will be made.

RTD with InGaAs/AlAs material system had been introduced by Inata et.al [8] in 1987 in order to improve peak current density as well as PVCR by increasing barrier even higher. Inata et. Al obtained a high PVCR of 14 for the first time [9]. Broekeart et. al obtained a higher PVCR of 23 in 1988 [10]. In 1995, Shimizu et. al obtained the highest peak current density of 680kA/cm^2 [11].

2.4 DC Characteristics of RTD

The tunneling effects in semiconductor lead to a phenomenon called the negative differential resistance. This was first suggested by Tsu and Esaki in 1973 [8]. The Current-Voltage data used in this research are obtained from double barrier resonant tunneling diode (DBRTD) grown by molecular beam epitaxy at Nottingham University [12]. Figure 2.7 shows typical IV characteristics of the RTD. The key characteristics of the RTD are the peak current, valley current as well as the PVCR.

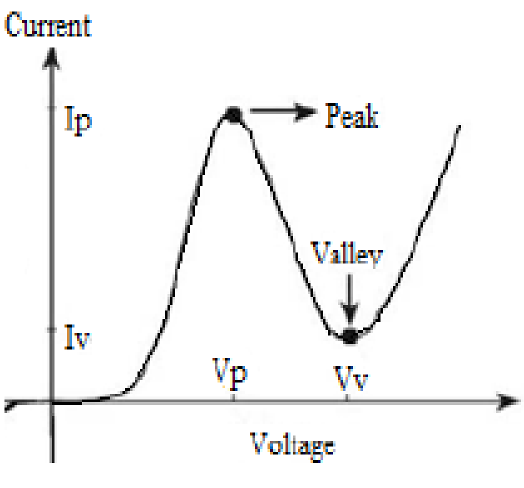

Figure 2.7 IV characteristic of DBRTD device with NDR. [13].

2.4.1 Negative Differential Resistance (NDR)

The most important property of an RTD lies in its NDR, which is sustainable to very high frequencies and offers very fast switching speed. The NDR is a phenomenon happening in RTD when the electrons pass through the barrier by tunneling method. This was first suggested by Tsu and Esaki in 1973 [6]. From Figure 2.7, shows the positive polarity of an Iv characteristic. NDR is happening in the region starts from the peak current to valley current. The region will lead to the formation of negative resistance as the formation of this region opposes the Ohm's law. PVCR is important in affecting the NDR. The greater the value of PVCR, the larger the region of NDR. Ideally, to have a large PVCR, the peak current, I_p must be large as possible while the valley current, I_v must be small as possible.

$$PVCR = \frac{I_p}{I_V} \qquad (2.1)$$

Even though too large peak current, I_p may be unreasonable due to the issue of high power dissipation because high peak voltage will produce high power dissipation. This can be solved by designing RTD with very low peak voltage, V_p in this research.

In double barrier quantum well (DBQW) RTD, there is device capacitance because it is an undoped region surrounded by heavily doped contact regions which approximated by:

$$C_d = \frac{A\varepsilon_0\varepsilon_r}{t} \qquad (2.2)$$

Where A is the area of the device, t is the thickness of the double barrier quantum well structure which consists of space, barrier and well layers. The permittivity of free space is given by ε_o and the relative permittivity of barrier and well materials is denoted by ε_r [3].

2.5 Structural Parameters of RTD

2.5.1 Barrier Thickness (t_b)

Barrier thickness is one of the parameters that can be considered to get the maximum performance of the RTD. It is worthy to employ a quantum mechanical point of view in order to understand the dependence of current density, J on barrier thickness, t_b. The resonant tunneling current through a double barrier quantum well structure depends on the transmission probability, T [14]:

$$T \alpha e^{-2Kt_b} \qquad (2.3)$$

Where the wave vector inside the barrier is given by,

$$K = \sqrt{(\frac{2m_b v}{h^2})} \qquad (2.4)$$

And m_b is the electron effective mass in the barrier at energies close to the conduction band edge of the emitter while V is the potential barrier. Therefore, as the barrier thickness reduces, the transmission probability, T and current density, J increase exponentially [3].

2.5.2 Spacer Thickness (t_s)

The reasons for the inclusion of the undoped spacer as shown in Figure 2.3 is to prevent diffusion of dopants to the subsequent layer during growth. The electron means the free path is clear from ionized donors with the presence of undoped spacer. Figure 2.8 shows a triangular well will be formed near the emitter barrier as illustrated in Figure 2.3 Example epilayer structure of RTD using InGaAs/AlAs material system studied in this project [3]. by having undoped spacer layer between the contact, said emitter and barrier, under large applied bias. The formation of this triangular well will promote the resonant tunneling between the quasi-bound state electron and the resonant state in the quantum well and consequently improve peak to valley current ratio (PVCR) [3].

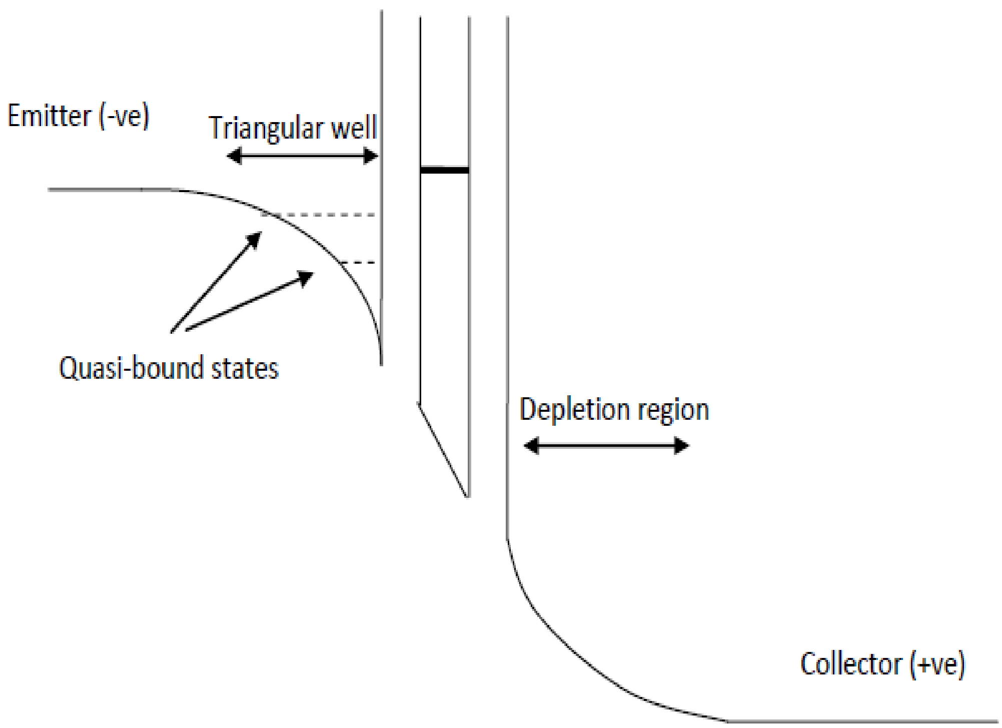

Figure 2.8 Schematic band diagram of RTD with spacer layer (low-doped/undoped) in both sides of barriers [6]

2.5.3 Quantum Well Thickness (t_{qw})

Beside barrier thickness, the quantum well thickness is another parameter that can be considered in order to get the maximum performance of RTD. The thickness of the quantum well is normally related to the quantization energy state, Er inside the quantum well. The quantization energy inside the quantum well can be expressed as:

$$E_n = (\frac{h^2\pi^2}{2m_w t_w^2})n^2 \qquad (2.5)$$

Where m_w is electron effective mass inside the quantum well, t_w is the thickness of the quantum well, h is reduced Planck' constant with the value of $1.054571800x10^{-34}$ J.s.

The relationship between the quantized energy and the quantum well thickness in inversely proportional from the equation. When the quantum well thickness is reduced, the quantized energy will increase. The peak voltage and peak current density will increase as the quantization energy increase. The higher quantization energy means that it takes a larger bias voltage to reach its peak and hence higher peak voltage. When the quantization energy inside the quantum well coincides with the conduction band offset, the peak voltage occurs. Therefore, RTD will have better performance with the use of narrow quantum well thickness.

Beside quantum well thickness, effective mass m_w also affect the quantization energy of the quantum well. The relationship between effective mass and quantization energy is inversely proportional to each other. The peak current of RTD will increase as the thickness of the quantum well decrease [18].

2.6 Application of Resonant Tunnelling Diode

2.6.1 Oscillator circuit

One of the applications of RTD device is an oscillator. RTD is suitable to be used as oscillator due to its ability to perform tasks at high speed up to Terahertz and the present of NDR region. RTD has been applied to some kinds of micro sensors and actuators. The basic idea in oscillators containing RTD behaves like a negative resistance and tries to cancel the resistance of the circuit to achieve sustained oscillations with ultra-high frequencies [15]. The oscillator circuit based on the RTD as shown in Figure 2.9 is the more importance factor on sensitivities and stability of the sensors.

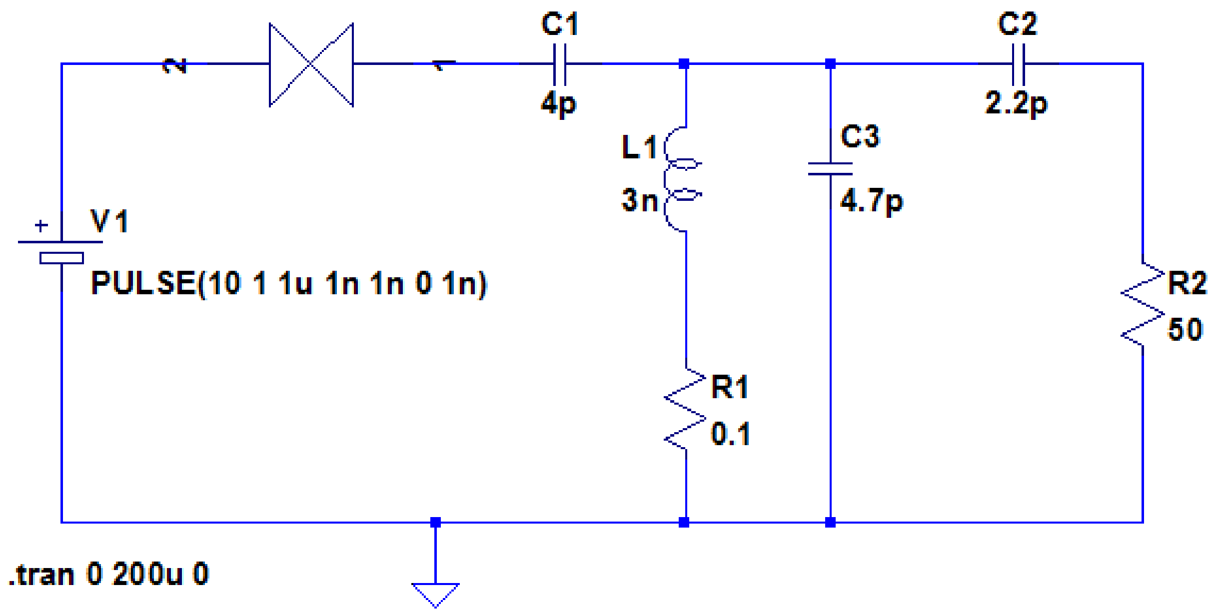

Figure 2.9 RTD based oscillator circuit

2.6.2 Frequency multiplier

The frequency multiplier as shown in Figure 2.10 is the example of a signal processing application based on such a device which increase their processing speed and reducing the processing time. The circuit requires only a load resistor (R_L) and an optional dc bias for an initial selection of the operating point in order to emphasize the reduced complexity of these circuits.

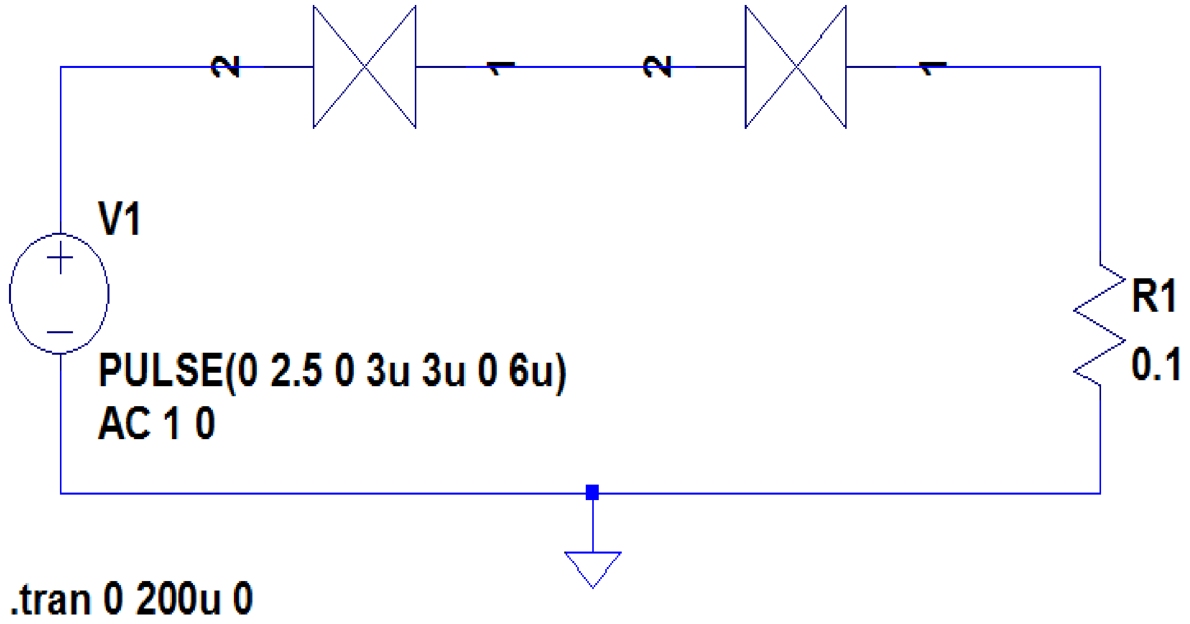

Figure 2.10 Frequency multiplier circuit.

2.6.3 Three-state Logic

Three-state logic is a circuit used in digital electronic which allows multiple circuits to share the same output. An output port which assumes a high impedance state remove the circuit if it were not connected at all. The circuit as shown in Figure 2.11

is a three-state inverter consisting of RTD combination, a capacitor to decouple the DC source (V_2) from the input (V_1) and two resistors for appropriate biasing.

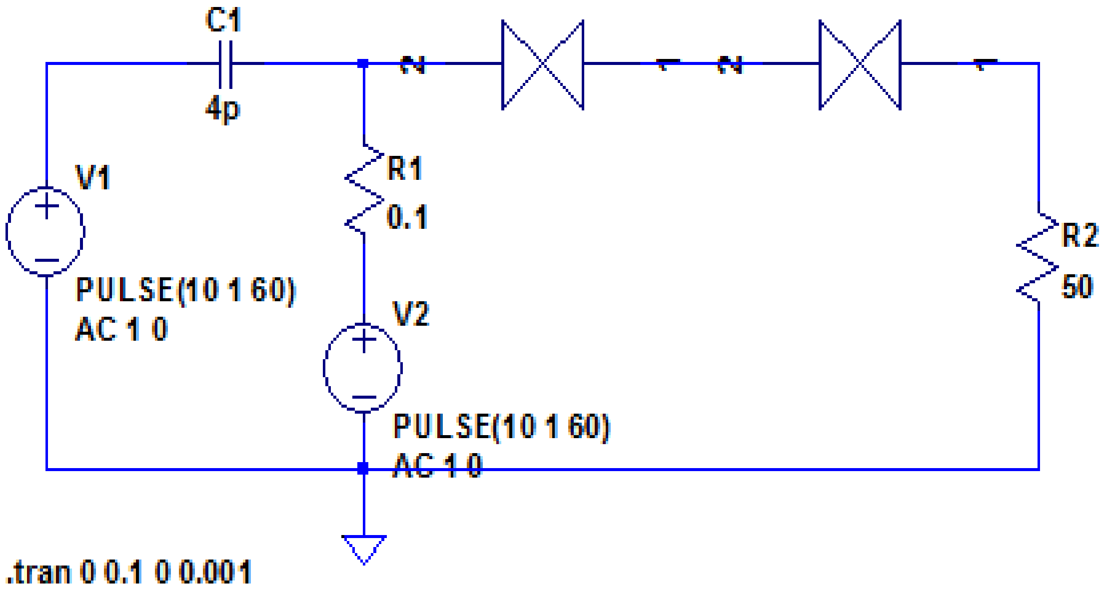

Figure 2.11 Three-state logic circuit.

CHAPTER 3 Methodology

3.1 Device Modelling using LTspice

In this section, the methodology of the device modeling using LTspice will be discussed. Using the analog behavioral modeling capabilities of LTspice, the current-voltage characteristics and the large signal equivalent circuit of a resonant tunneling diode are exploited to create an LTspice compatible model for the diode. There are three methods to model the IV characteristics of the RTD device, which are the polynomial, transfer function, and lookup table.

3.1.1 Polynomial Method

The polynomial method involves plenty of polynomial mathematical equation with certain, n^{th} to plot or simulate the IV curve. Usually, the RTD with a high order polynomial equation will fit the IV curve. A 15^{th} order polynomial was an example to obtain an acceptable range to fit the IV curve.

3.1.2 Transfer Function Method

Transfer function method involves the mathematical expression of the transfer function in standard notation. The function specified by the mathematical expression of the signal will perform by the input signal, whereas, the result on the output pins will perform by the output signal. The well-known Breit-Wigner formula of electron transmission through a double barrier structure described in Equation 3.1 the large signal RTD behavior [12]:

$$I = f\{C_1V[tan^{-1}(C_2V + C_3)] - [tan^{-1}(C_2V + C_4)] + C_5V^m + C_6V^n \qquad (3.1)$$

Where C_i are constants related to the peak and valley currents and voltages, *f* is a scaling factor and *m* and *n* are integers.

3.1.3 Lookup Table Method

The table method part uses a table consisting the measured voltages and currents to describe a transfer function. The lookup table method will be used in this research to model the RTD device as the values used in this method are from the measurement of the RTD device obtained from the experiment. Therefore, as compared to the other two methods, the result using lookup table will be more precise.

In general, the SPICE model for RTD device as shown in Figure 3.1 was studied and was is drawn in LTspice to simulate the large signal representation. The IV curve of RTD was obtained from the simulation in the LTspice. Before the simulation, the value of capacitance and resistance need to be determined from Equation 3.2 and Equation 3.3 [17]:

$$C_{rtd} = \frac{\varepsilon_0 \varepsilon_r A}{d} \qquad (3.2)$$