Resonant Tunnelling Diode Design for Oscillator Circuit

Halimatus Saadiah\(^3\), Warsuzarina Mat Jubadi\(^1,3^{*}\), Nabihah Ahmad\(^1,2,3\), M. Hairol Jabbar\(^2,3\)

\(^1\) Nano Simulation Research Group, FKEE, UTHM
\(^2\) IC Design Research Group, FKEE, UTHM
\(^3\) Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, Malaysia.

\(^*\) Email: suzarina@uthm.edu.my

Abstract. Resonant Tunneling Diode (RTD) was introduced by Tsu and Esaki in 1973 and it is a p-n junction device that exhibits Negative Differential Resistance (NDR). Due to the NDR and its characteristics, RTD is suitable for high speed application device especially in the oscillator circuit. The fast-acting negative differential resistance of RTDs make them excellent devices for very high-frequency electronic applications. An NDR region is an important region at which an oscillation will occur. Therefore, this study perform a simulation of RTD design for oscillator circuit at a target frequency of 500 – 600 GHz. In this research, the simulation of I-V characteristics for RTD device and oscillator characteristics are performed in MATLAB. The C-V characteristics are identified and simulated in order to define the frequency value. It can be observed that a smaller capacitance value is required in order to obtain higher frequency oscillation. The target frequency oscillation at around 500-600 GHz have been achieved through the simulations of the RTD design.

1. Introduction

Today’s technology has been developing very fast. Because of that, new and advanced devices that offer a different application at high frequency and function are produce every year. Resonant Tunneling Diode (RTD) was discovered about two decades ago and it gives an advantage in developing of electronic device. Its special characteristics lies on its structure, operation and the Negative Differential Resistance (NDR) region which make RTD very significant for high speed application; for example, oscillator circuit [1]. Besides, RTD is suitable for high switching speed because of its small capacitance and high current density and effectively functional at the room temperature [2].

Tunneling diodes can be very compact and are also capable of ultra-high-speed operation because the quantum tunneling effect through the very thin layers is a very fast process. Because of that, RTD structures is used as an oscillator with operating frequencies as high as 712 GHz and a mixer with operating frequency of 2.5 THz [2]. The oscillations are due to the Direct Current (DC) instabilities
caused by the RTD inductance value, the shape of the RTD current-voltage characteristic and the bias voltage [1].

Oscillator circuit is very important in communication system such as in radio, and computer. An oscillator functions to generate a signal in computer or electronic devices. If this oscillator generates a signal with higher frequency, so electronic devices will have faster performance. Hence, oscillator circuit is designed by using RTD due to its excellent performance at very high frequency. The fast-acting negative differential resistance of RTDs make them admirable devices for very high-frequency electronic applications [1]. Therefore, the purpose of this study is to perform the simulation of resonant tunneling diode which is designed for oscillator circuit at around 500-600 GHz.

2. Circuit Design

2.1 RTD Circuit and Characteristics

RTD is an undoped quantum well, sandwiched between two undoped layers of barrier and the doped region are collector and emitter. Besides, RTD is operated in electron tunneling mechanism or known as quantum mechanical tunneling [5]. The phenomenon of resonant tunneling happen when the electron transmission coefficient is drastically increasing in equivalent of particular energy values [6]. The passing of electrons through a barrier which is very thin compared to the electron wavelength is known as quantum tunneling process [5].

There are two characteristics of RTD; C-V and I-V characteristics respectively. These characteristics are depending on the circuit that has been chosen. Figure 1 displays two types of small signal equivalent circuit for RTD; the G-C equivalent circuit and parallel-inductance equivalent circuit. Figure 1(a) shows the simplest circuit of RTD which consists of a parallel combination between conductance capacitance (G-C equivalent circuit). However, this circuit is not suitable for RTD at high frequency due to the real and imaginary parts of RTD admittances. The RTD conductance and capacitance does not change with frequency, instead of having a constant value [2]. Second type of circuit is shown in Figure 1(b) which is parallel-inductance equivalent circuit and it is chosen as the RTD circuit.

![Figure 1. Small signal of equivalent circuit of RTD [3]](image)

Figure 2 shows the graph of C-V characteristics for RTD. A capacitance value has a relationship with the voltages whereas the voltage further increase above 0.2 V, the capacitance will drop drastically as parabolic curve. It indicates the decreasing of charge density [10]. It means that voltage value will affected the capacitance value in RTD. Besides, the graph shows that the higher frequency of RTD i.e., 30 GHz will have smaller capacitance value as compared to frequency of 10 GHz. The graph in Figure 3 demonstrates the real part of the input admittance (conductance) versus the bias voltage at different frequencies. It has the same curve with capacitance graph but inversely to the shape of graph in Figure 3.
2. Hence, it confirm that the frequency is dependence on the differential conductance, \( G \) and capacitance, \( C \) especially in the NDR region [2].

![Figure 2. Equivalent capacitance versus the bias voltage at different frequencies.](image1)

**Figure 2.** Equivalent capacitance versus the bias voltage at different frequencies [2]

![Figure 3. Real part of the input admittance (conductance) versus the bias voltage.](image2)

**Figure 3.** Real part of the input admittance (conductance) versus the bias voltage [2]

### 2.2 Oscillator Circuit Based on RTD

An oscillator circuit consists of a voltage supply, a serial inductor, an RTD, and a capacitor are required in designing of oscillator as shown in Figure 4. Furthermore, DC instabilities will cause oscillations due to the shape of the RTD current-voltage characteristic and bias voltage. The rising and failing time of the oscillator voltage edges will be determined by capacitance values. However, the capacitances have minor effect on the frequency as compared to the inductance [1].

![Figure 4. Schematic of RTD oscillator circuit.](image3)

**Figure 4.** Schematic of RTD oscillator circuit

The RTD based oscillator circuit produces a Terahertz signal source. This oscillator will have highest maximum oscillation frequency \( f_{\text{max}} \) of the inherent Negative Differential Conductance (NDC) due to the resonant tunnelling among the electronic devices [7]. The improved performance of practical
operation in microwave frequency is achieved by RTD oscillator topologies demonstrated in [7]. Besides, the size of RTD based oscillator circuit is small and this reduces power loss of devices [6].

3. Simulation Parameters

The tunneling current for RTD device can be derived from equation (1) - equation (3). It is calculated based on integrating the transmission electron velocity over the electron distribution in k space [5]. Besides, these equations are also used for modelling RTD. Meanwhile, figure 2.10 illustrates the result after the derivation of tunneling current. This figure show the current density based on sample presented in WM Jubadi [5].

\[ J = \frac{em^*kT}{4\pi^2h^2} \int_0^\infty dE T(E,V) \ln \left[ \frac{1+e^{(E_F-E)/kT}}{1+e^{(E_F-E-V)/kT}} \right] \]  
\[ \tau(E,V) = \left[ \frac{1}{2} \right]^2 \left[ E - \left( \frac{E_r - eV}{2} \right) \right]^2 + \left[ \frac{1}{2} \right]^2 \]  
\[ J = \frac{em^*kT}{4\pi^2h^2} \ln \left[ \frac{1 + e^{(E_F+E_r+eV/2)/kT}}{1 + e^{(E_F-E_r+eV/2)/kT}} \right] \left[ \frac{\pi}{2} + \tan^{-1}\left( \frac{E_r - eV}{\frac{\Gamma}{2}} \right) \right] \]  

Where \( \Gamma, E_r, E_F, m^*, h \) are the resonance width, the energy in the In0.8Ga0.2As well resonance level, the energy of the Fermi level in two contacts, the effective mass and the reduced Plank constant, \( E \) is the energy of the resonant level relative to the bottom of the well at its center [5].

In this research, Equation (4) - Equation (7) were obtained from Abdallah, R. M., Dessouki, A. A., & Aly, M. H. [8] to model the I-V characteristics of RTD device. Therefore, these equations are used for fitting the graph of current density of the RTD device. The parameter of \( A, B, C_1, D_1 \) and \( E_1 \) in this equation indicates different I-V characteristics of RTD device. Besides, parameter \( C_2 \) is used to control the height of the added inverse tangent term. \( D_2 \) is used to control the slope of this function, and consequently, can change the slope of the negative differential conductance. Lastly, \( E_2 \) controls the voltage of the middle point of the tangent function [8].

\[ I_{\text{exponential}}(V) = A \times e^{(B \times V)} - e^{(-B \times V)} \]  
\[ I_{\text{Gaussian}}(V) = C_1 \times e^{(-D_1(V - E_1)^2)} - e^{(-D_1(V + E_1)^2)} \]  
\[ I_{\text{mod}}(V) = C_2 \times (\tan^{-1}(D_2(V - E_2)) + (\tan^{-1}(D_2(V + E_2))) \]  
\[ I(V) = \text{area} \times (I_{\text{exponential}}(V) + I_{\text{Gaussian}}(V) + I_{\text{mod}}(V)) \]  

4 Results and discussion

4.1 I-V Characteristics of RTD

In this study, four simulations of I-V characteristics are illustrated in one graph as show in Figure 5. Based on the graph, it shows the different value of peak and valley for current and voltage when the parameter of fitting are varied. Therefore, all these value have been summarized in Table 1. Based on the table, it is obvious that simulation 2 has higher Peak to Valley Current Ratio (PVCR) value but lower peak current. However, simulation 4 has higher
peak current value compare to other simulation. So, it is indicated that simulation 4 is better simulation because the higher peak current value can be affected the oscillator frequency. It is evidence that parameter A, C₁ and C₂ are significant in order to achieve different peak current value. The pattern of I-V characteristic graph is the same with the previous study in [5]. Therefore, it is proven that the fitting value is tolerable.

![Graph I-V Characteristics for combination of simulation 1-4](image)

**Table 1: Result of peak and valley value for current and voltage.**

| Simulation | Current (A) | Voltage (V) | PVCR |
|------------|-------------|-------------|------|
|            | Iₚ          | Iᵥ          | Vₚ   | Vᵥ   |      |
| 1          | 7.315       | 6.042       | 0.34 | 0.46 | 1.21 |
| 2          | 14.27       | 11.57       | 0.34 | 0.46 | 1.23 |
| 3          | 16.00       | 13.20       | 0.34 | 0.46 | 1.21 |
| 4          | 16.46       | 13.86       | 0.34 | 0.46 | 1.20 |

### 4.2 C-V Characteristics

In this study, C-V and G-V value for 4 simulations are plotted in one graph as illustrated in Figure 6. Besides, Figure 7 shows the reciprocal of inductance versus voltage that will be used in the oscillator circuit in Figure 4. However, it will be omitted for the calculation at the higher frequency because the graph shows that inductance have very a small value and less significant [8-10]. Based on Figure 6(a) and Figure 6(b), one simulation point of conductance and capacitance value in each simulation has been chosen which is at V=0.34V. The findings are simplified and tabulated into the Table 2 in order to relate with the frequency of oscillation. This voltage value is chosen because it is around NDR region which reside between at the peak voltage and valley voltage.
Figure 6. (a) G-V Characteristics and (b) C-V Characteristics for combination of simulation 1-4

Figure 7. Graph reciprocal of inductance for combination of simulation 1-4

Table 2: Component values for oscillation frequency calculation

| Simulation | G(S)    | C (F)   | L (H)   |
|------------|---------|---------|---------|
| 1          | 2.2853  | -1.7761p| 1.1290p |
| 2          | 2.7231  | -2.1220p| 0.94744p|
| 3          | 3.6792  | -2.8773p| 0.70124p|
| 4          | 5.2921  | -4.1514p| 0.48752p|

The value of conductance and capacitance tabulated in Table 2 are used in order to calculate frequency for oscillator. Therefore, Figure 8 demonstrates the frequency versus voltage for various parameter values define in Eq (1) – Eq. (4). The graphs shows that the frequency value is dependent on the conductance value as it has the same G-V characteristics. The oscillation will occur at the NDR region where it is defined at V=0.34 V. Then, the frequency value from the simulations are summarized into Table 3. Based on the analysis, the capacitance and conductance had influenced the frequency value of oscillator circuit [11-12]. The frequency is higher when the conductance value is higher and lower capacitance value. It is observed that the capacitance value should be kept lower in order to get a higher oscillation frequency. Therefore, the best RTD design for oscillator is simulation 4 because it is achieved the targeted frequency which is 557.13 GHz.
Figure 8. Frequency versus Voltage.

Table 3 Capacitance and Frequency value at V=0.34V (NDR of RTD device)

| Simulation | G (S)  | C (pF)  | F(GHz)  |
|------------|--------|---------|---------|
| 1          | 2.28   | -1.78   | 254.48  |
| 2          | 2.72   | -2.12   | 298.51  |
| 3          | 3.68   | -2.88   | 394.74  |
| 4          | 5.29   | -4.15   | 557.13  |

5 Conclusion

Resonant Tunneling Diode (RTD) has been successfully design for oscillator circuit with targeted frequency which is 500-600 GHz. In order to achieve the target frequency, a few simulations have been conducted. The best result is illustrated in simulation 4 obtained by using A, B, C₁, C₂, D₁, D₂, E₁ and E₂ parameter value of 29.6695x10¹¹ A/m², 2.3545 V⁻¹, 25.1813x10¹¹ A/m², -18.9879x10¹¹ A/m², 15.5466 V⁻², 15.5470 V⁻¹, 0.3227 V and 0.4028 V respectively. Besides, simulation 4 has a higher peak current value as compared to other simulations which is 16.46A and the PVCR is 1.20. Based on simulation, the frequency is increased when conductance value increases and meanwhile the capacitance value is decreases. Therefore, the conductance and capacitance value of 5.2921S and -4.1514 pF to achieve an oscillation frequency of 557.13 GHz. In conclusion, oscillator circuit based on RTD is successfully designed based on this value.

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