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Effect of Structural Parameters on Current-Voltage Properties of GaAs-based Resonant Tunneling Diodes Using Device Simulator

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ABSTRACT

The resonant tunneling diode (RTD) was first introduced by Tsu and Esaki back in 1973. The RTD has a nano-meter scale dimension and is capable to operate in the terahertz range of frequency, thanks to its unique negative differential resistive (NDR) property. There are tons of potential of RTD capable to implement in many applications if the optimum scales and parameters of the RTD's structure can be determined. Hence, this is the reason and purpose of this work being conducted. The effects of structural parameters of RTD are studied and analyzed. From the simulation results generated by the WinGreen simulator, the barrier layer thickness has exhibited to be the most performance-affective structural parameter for RTD, when compared to other parameters such as thicknesses of spacer and quantum-well layers, and doping concentration of emitter and collector layers. The highest peak-to-valley current ratio (PVCR) of InGaAs/AlAs RTD achieved is approximately 78.36 with its barrier layer thickness of 1.6 nm. For GaAs/AlAs RTD, the highest PVCR obtained is approximately 59.29 at 1.6 nm thick of its barrier layer.

Keywords: Peak-to-valley current ratio, resonant tunneling diode, simulator

1. INTRODUCTION

The idea of resonant tunneling diode (RTD) was figured by Tsu and Esaki back in 1973 [1] and the first RTD was designed and constructed by Chang et al. in 1974 [2]. An RTD is a double- barrier quantum well (DBQW) heterostructure diode that consists of a quantum well placed in between two thin undoped barrier layers with a large bandgap [3, 4]. The device has been realized using several heterostructure materials including InGaAs/AlAs [5], GaAs/AlAs [6] and AlN/GaN [7]. An RTD operates under the tunneling effect principle and it has unique negative differential resistance (NDR) properties [4, 8]. Due to these characteristics, RTD can operate at a very high frequency and relatively low power consumption [6]. Besides, the size of an RTD can also scale down to a nanometer range while capable of functioning stably at room temperature [9, 10]. Hence, it is worthwhile to investigate, analyze, and improve the RTD as it might be a crucial component to make ultra-high-speed applications possible.

One of the important parameters that can determine the performance of an RTD is the peak-to-valley current ratio (PVCR) which quantifies the ratio between the peak current, IP, and the valley current, IV, in the NDR region. A high PVCR is always preferred to achieve the desirable device performances [11]. As such, the aim of this project is to analyze and evaluate the effect of structural parameters of GaAs-based RTDs on the PVCR properties which can be useful in designing RTDs to obtain the desired PVCR values. This is done by conducting the simulation of the RTDs using WinGreen simulator. The PVCR properties of the RTDs can then be obtained from the current-voltage (I-V) characteristics of the devices. The recent experimental and calculated PVCR values for InGaAs/AlAs RTDs can achieve up to 28 and 86, respectively [11].

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2. DEVICE STRUCTURE AND MODELLING

The current density of the resonant tunneling diode, J can be expressed as [12],

$$J = \frac{q}{2\pi h} \int N(E)T(E)dE \tag{1}$$

where q, $\hbar$ and E are the electron charge, Planck constant and energy level, respectively. T(E) is the tunneling probability and N(E) is the number of electrons which can be written as,

$$N(E) = \frac{kTm*}{\pi h^2} \ln\left[1 + \exp\left(\frac{E_F - E}{kT}\right)\right] \tag{2}$$

where k, T, m^*, and E_F are wave vectors in the quantum well of the RTD, temperature, effective mass, and energy of the Fermi level, respectively. Equation (2) describes the number of available electrons for tunneling from the emitter across the RTD.

If the incoming energy to the RTD does not meet the quantized energy level, E_n, the T(E) can be expressed as,

$$T(\mathrm{E}) = T_\mathrm{E} T_\mathrm{C} \tag{3}$$

where T_E and T_C are the tunneling probability between well and emitter, and between well and collector, respectively. On the other hand, if the incoming energy matched to any of E_n in the quantum well of the RTD, the T(E)becomes,

$$T(E = E_n) = \frac{4T_E T_C}{(T_E + T_C)^2} \tag{4}$$

As mentioned earlier, in this work, the PVCR is used to determine the performance of an RTD which can be written as, PVCR = I_P/I_V. The value of I_P and I_V can be obtained from the simulated I-V characteristic of the respective RTD as shown in Figure 1.

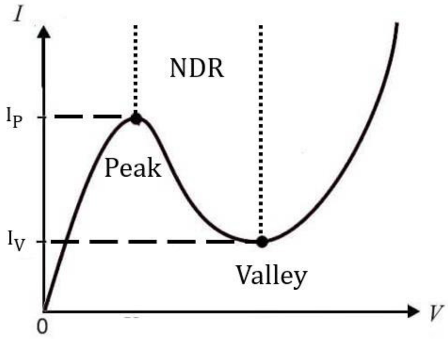


Figure 1. A typical I-V characteristic of RTD with negative differential resistive (NDR) property. The I_P and I_V can be obtained from the graph in order to calculate the PVCR value of the RTD.

There are two structures of GaAs-based RTDs that have been simulated in this work using the WinGreen simulator as shown in Figure 2, which are InGaAs/AlAs and GaAs/AlAs. Both RTD structures consist of several layers which include emitter, collector, spacer, barrier, and quantum well with their respective thicknesses and doping concentrations. The simulator has been validated based on the InGaAs/AlAs RTD structure used in ref. [13]. The obtained simulation value for the peak current density at applied voltage of 1 V is within the same order of magnitude.

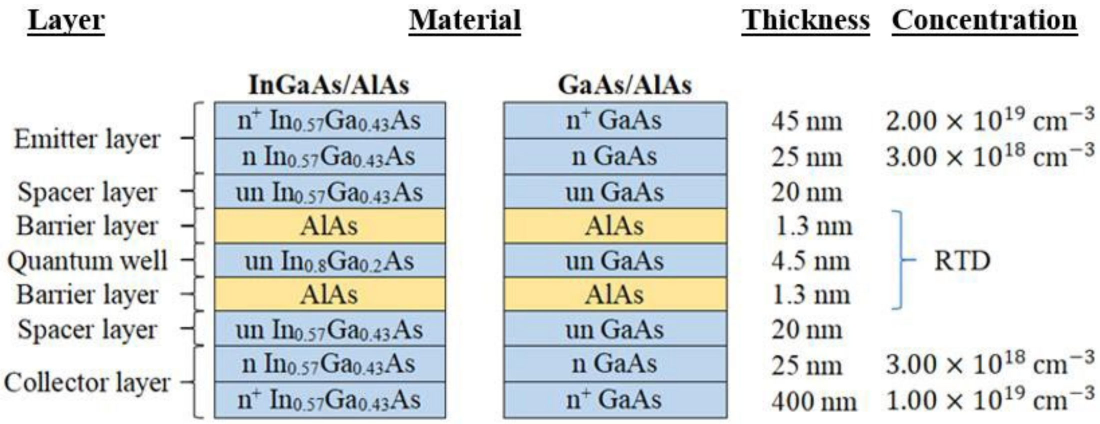


Figure 2. Structures of RTDs with their corresponding layers, materials, thicknesses, and concentrations.

3. RESULTS AND DISCUSSION

Table 1 shows the comparison of I-V characteristics for both InGaAs/AlAs and GaAs/AlAs RTDs with varying structural parameters of the devices. This includes thicknesses of quantum well, spacer and barrier layers, and doping concentrations of emitter and collector.

The quantized energy level in the quantum well, En can be expressed as,

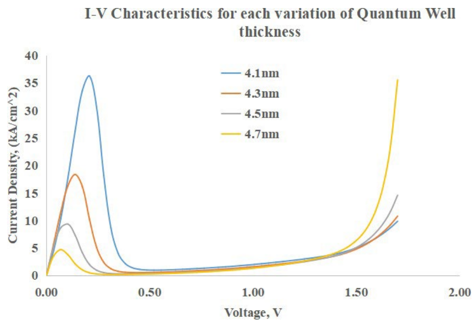
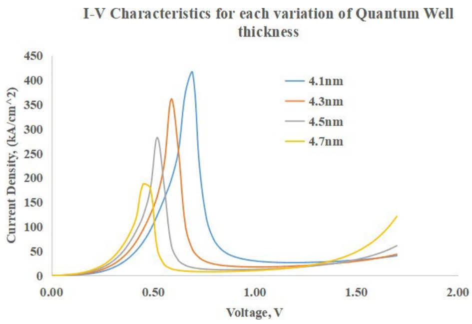
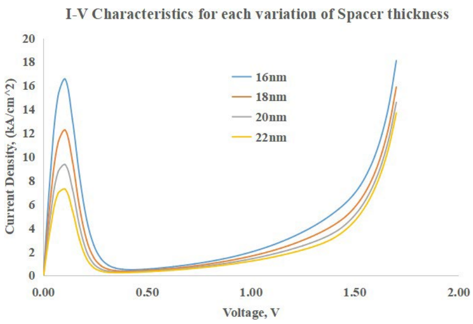
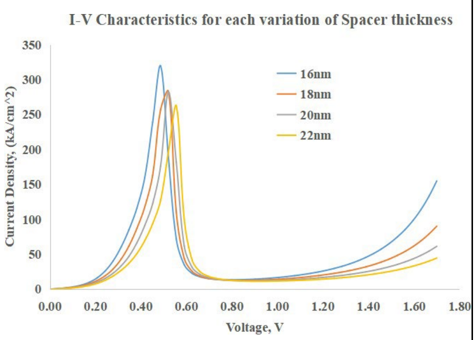
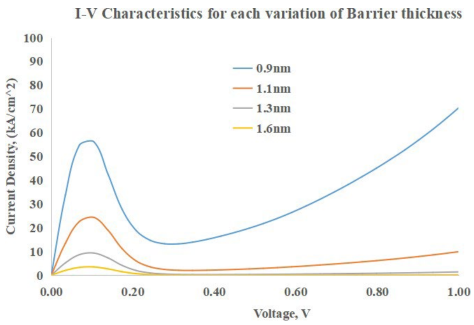
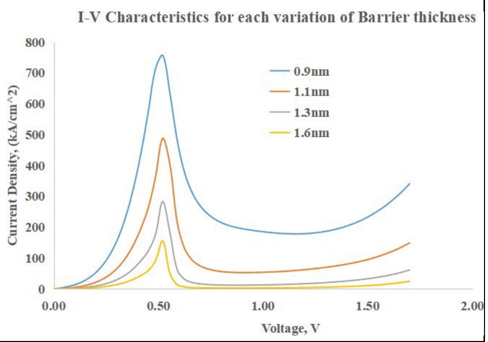
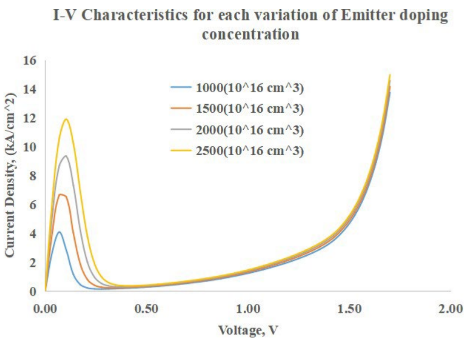
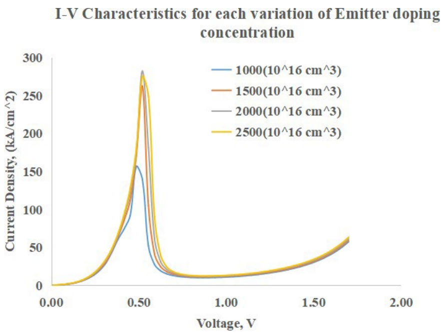
$$E_n = \frac{h^2}{2m*_w}\left[\frac{n\pi}{d}\right]^2, n = 1,2,\ldots \qquad (5)$$

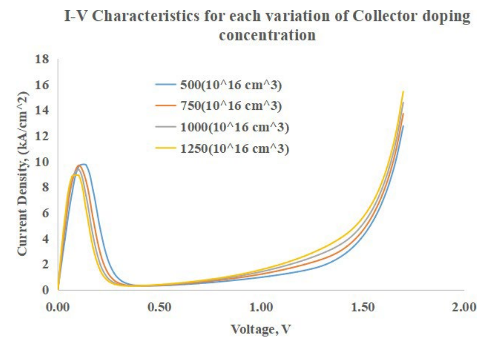
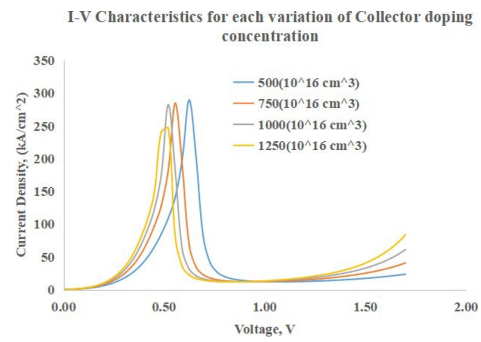
where m*W is the electron effective mass inside the quantum well and d is the width of the well (i.e., the quantum well thickness).

From Equation (5), the spacing between energy levels increases as d reduces. This requires more energy (i.e., higher applied voltage) for the resonant tunneling effect to take place in the devices. This is the reason why the peak current density has shifted significantly to the right as the quantum well thickness reduces as can be seen in Table 1 for both InGaAs/AlAs and GaAs/AlAs RTDs. In addition, the quantum well thickness parameter affects both RTDs differently. As this parameter increases, the peak current density and valley current density of both RTDs are reduced. However, the magnitude of peak current density and valley current density of the InGaAs/AlAs RTD is much smaller when compared to the GaAs/AlAs RTD. Hence, the PVCR of InGaAs/AlAs RTD reduces gradually unlike the PVCR of GaAs/AlAs RTD which increases with the increasing quantum well thickness. This might be due to the difference between electron effective mass and electron mobility of the InGaAs and GaAs materials [11].

For the spacer layer, the increased spacer thickness reduced the PVCR of both RTDs because the magnitude of the peak current density has dropped more significantly than the valley current density. This might be due to the decreased probability of resonant tunneling to occur caused by the increased number of closely spaced resonant states in the spacer layer. A larger number of these resonant states in the spacer layer reduces the probability of aligning them with the energy levels in the barriers. The PVCR of InGaAs/AlAs RTD drops approximately 3 %, and the PVCR of GaAs/AlAs RTD has a less significant drop (remains approximately at 23).

Table 1 I-V characteristics of InGaAs/AlAs and GaAs/AlAs RTDs with varying parameters

Parameters	InGaAs/AlAs RTD	GaAs/AlAs RTD
Quantum well thickness		
Spacer layer thickness		
Barrier layer thickness		
Emitter layer doping conc.		

Collector layer doping conc.		

For the barrier layer, the peak current density of both InGaAs/AlAs and GaAs/AlAs RTDs is reduced greatly with the increasing of the barrier thickness. This is expected as a thicker barrier layer contributes to a lower number the electrons that can tunnel through the energy barriers. However, there is a smaller reduction of the valley current density as the barrier thickness increases when compared to the reduction of the peak current density. This leads to a higher value of PVCR for both InGaAs/AlAs and GaAs/AlAs RTDs with the increasing of the barrier thickness. The PVCR of InGaAs/AlAs RTD is almost doubled, and the PVCR of GaAs/AlAs RTD increased more than 117 % as the barrier layer thickness increases by 0.2 nm. The highest PVCR values achieved for InGaAs/AlAs and GaAs/AlAs RTDs are 78.36 and 59.29, respectively, with barrier thickness of 1.6 nm.

The increase of the doping concentration of the emitter layer results in an increase of the PVCR of both RTDs, but the effect is relatively minor. An increase of 500×10^{16} cm^3 doping concentration just leads to an increase of approximately 3 – 6 % of the PVCR of the InGaAs/AlAs RTD. The optimum amount of the emitter doping concentration for GaAs/AlAs RTD is $2{,}000 \times 10^{16}$ cm^3. This is because as the doping concentration of the emitter layer increases beyond this value, the PVCR of the RTD starts to drop by a little. Lastly, the increasing doping concentration of the collector layer results in a gradual decrease in the PVCR of both RTDs. However, the effect is minor. An increase of 250×10^{16} cm^3 doping concentration reduces approximately 0.6 to 5 % and 0.3 to 12 % of the overall PVCR for InGaAs/AlAs RTD and GaAs/AlAs RTD, respectively.

4. CONCLUSION

Both InGaAs/AlAs and GaAs/AlAs RTDs show a similar effect on the I-V characteristics by varying their structural parameters except for the quantum well thickness. The thicker the quantum well, the higher the PVCR of the GaAs/AlAs RTD but the PVCR for InGaAs/AlAs RTD is decreased. The most dependent parameter of both RTDs is the barrier layer thickness. A small increase in the barrier layer thickness can result in a tremendous increase in the PVCR of both RTDs. However, the increasing barrier layer thickness also leads to a lower peak current density which may not be suitable for high power applications. For the rest of the parameters, their effect on the PVCR of the RTDs are relatively minor. For the spacer layer, the increase in the spacer layer thickness leads to a minor decrease in the PVCR of the InGaAs/AlAs RTD. The effect is less sensitive for the GaAs/AlAs RTD in which the PVCR remains approximately the same as the spacer layer thickness increases. Lastly, both RTDs show almost similar trends on the PVCR performance for the effect of the emitter and collector layer doping concentration. The simulation result shows that the higher the doping concentration of the emitter layer, the bigger PVCR of both RTDs can be attained. On the other hand, the increase in the collector layer doping concentration leads to a small reduction in the PVCR for both RTDs. Even though a high PVCR is desired especially for high power applications, when designing the optimum structure of RTDs, a reasonable value must be achieved between PVCR and the tunneling current density of the devices.

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