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Comparative Study of Single and Double Barrier GaAs Based Resonant Tunneling Diodes Considering NEGF

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***Abstract*—Growth of pepped up determining demand of final consumers always forces devices and circuits to increase power and speed., only resonant tunneling diode can solve this problem and can be able to take a vital role in many nanoscale applications. This research paper demonstrates the simulations of the Resonant Tunneling Diode (RTD) by using Hartree Model for the single barrier (1B) and the double barrier (2B) Resonant Tunneling Diodes by the using of NEMO5 considering NEGF. In addition, switching applications also require Large Peak to Valley Voltage Ratio (PVVR) to reduce energy loss. In this article, it is been clearly explained that compared to the Thomas Fermi Model, Hartree Model improves the Peak to Voltage Valley Ratio (PVVR) by 21.21%. The results that are found with the Double Barrier RTD showed much better performance than the Single Barrier RTD. Furthermore, the I-V characteristic verified the notable improvement for Hartree model.**

***Index Terms*—Resonant Tunneling Diodes, Hartree model NEGF, Lorentzian approximation NEMO5, PDR1, PDR2, NDR, Quantum Sheet Charge Density, Resonance Energy.**

I. Introduction

Difficulties for continual Complementary Metal Oxide Semi-Conductors have brought about explorations to substitute constructions for the capable, high speed operated and less powered upcoming logic devices. Resonant Tunneling Diode is an example of the evident gadget, which impressed an intense profit for possessing THz capabilities, negative differential resistance region and low voltage operation. The principle of quantum mechanical tunneling of electrons is operated by RTD into states of quantized well via a potential barrier in the transmission features that results in resonance. Transportation of simulation models are needed to describe RTD characteristics because the quantum mechanical nature of the tunneling process. This research paper used software where non-equilibrium green function formalism was present with use of approached effective mass and used to study Gallium Arsenide/Gallium Aluminum Arsenide RTD features. Scattering in the emitter region has been treated to ease computational burden in an approximate manner.

To represent a RTD, three equivalent proposals are worked out which include non-equilibrium Green function scheme, Schrodinger equation method and Winger equation [1]. Electrons are supposed on condition of composition where information are obtained by the chemical potential of the entrance regions. With the support of the open boundary conditions, all the states are found. At the hartree level, the interaction of electrostatic force is taken into account. In a less particular way with thomas fermi approximation, the coherent property is promoted.[1].

A very strongly creative and calculative model is provided by the no-equilibrium Green Function formalism for the use of quantum transport in high tech [2] [3-9]. To add the inflexible scattering and powerful effects of correlation at an atomics level, it excels the Landauer proposition for choleric, non-interacting electronics.

Double barrier RTD structures recently can be analyzed by Transfer Matrix Method (TMM)[10]. The numerous applications of RTD can be applied in both digital and analog circuits[11].

A huge diversity of uses in communication and electronic fields are demonstrated by the diodes of nano-scale size, for example, inert optics, and different sensor applications[13]. For reaching the highest frequency of 2.2THz in contast with the traditional Complementary Metal Oxide Semiconductors (CMOS) and Transistors which have 215 GHz. Nano

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computerized instruments demand lower current[12].RTD recline low power but high density is present in integrated circuits. By using few electrons, possible ultra lower power operation occurs at ambient temperature[12].In this paper, the single and double barrier RTD are fully designed in a new way for the evaluation of the performance.All of the simulations are based on Hartree Model provided better performance compared to Thomas-Fermi model.

II. RTD Modeling Approach

This article concentrated on two different types of RTD structures - single barrier RTD & double barrier RTD, as well as introducing two different types of model, that is, Thomas-Fermi and Hartree model. Contrast between two prototypes are mainly that thomas-fermi model do not have a quantum charge inside the quantum well but hartee model has quantum charge inside the quantum well. That is why, hartree model gives a elevated current in comparison with thomas model, but it has some hinderances because its NDR region has very poor performance in some conditions. Single barrier RTD had undoped barrier sandwiched between two low doped spacers.substantial number of electrons are supplied by two heavily doped contacts. No quantum well exists in single barrier, that is why it cannot provide NDR phenomenon. One barrier RTD composition is given below.

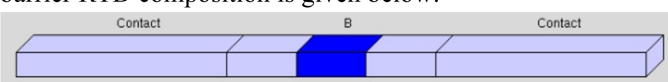

Fig. 1: Single barrier Resonant Tunneling Diode.

Double barrier RTD has an undoped quantum well is sandwiched between two barriers and large electrons' amount are supplied by two heavily doped contacts. A high level of impurity scattering are dramatically increased by the high doping. This high impurity level can demolish the consistency of waves of electrons in a well which is necessary for the transmission of resonance. RTD composition is given below.

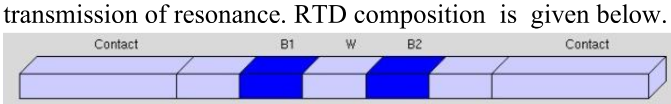

Fig.2: Double barrier Resonant Tunneling Diode.

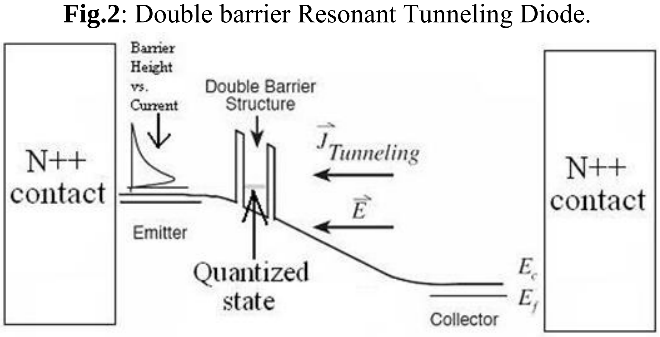

Fig. 3: Structure of the RTD [14, 15] and Corresponding Conduction Band Diagram under Forward Bias.

Fig. 3 represents structure of the RTD [14] [15] and diagram of the corresponding band conduction in forward bias. Quasi-Bound region is shown by shaded area of double barrier structure on a quantum well. In the emitter, the distribution of energy of the barrier height vs current is also shown.

If it is possible to keep strong quantum confinement between the barriers then inside the well gives many quantized energy or pseudo-driven state level(Fig.3) compared to previous one. Below table 1 shows different doping quantities as well as thickness and device length of this RTD.

Table 1: GaAs/AlGaAs DBRTD structure used in the simulations

Layer	**Material**	**Doping(/m^3)**	**Length (Angstrom)**
Spacer1	GaAs	1×10^{24}	100
Lead1	GaAs	1×10^{27}	300
Barrier1	AlGaAs	1×10^{24}	50
Well1	GaAs	1×10^{24}	50
Barrier2	GaAs	1×10^{24}	50
Lead2	AlGaAs	1×10^{27}	300
Spacer2	GaAs	1×10^{24}	100

When the RTD works on positive differential region for second time and when current equal to I_p , then the voltage across RTD is called the second voltage V_S. The important RTD parameters are[16]:

$$R_{p2} = \frac{V_s - V_v}{I_p - I_v} \quad (1)$$

$$R_{p1} = \frac{V_p}{I_p} \quad (2)$$

$$PVVR = \frac{V_p}{V_v} \quad (3)$$

$$|R_n| = \frac{V_v - V_p}{I_p - I_v} \quad (4)$$

$$PVCR = \frac{I_p}{I_v} \quad (5)$$

Here, peak to valley voltage ratio and peak to valley current ratio are PVVR and PVCR. The first and second positive differential resistances are R_p1 and Rp2.

In this work, we got R_{p1}=5.32 kiloohm, R_{p2}=4.0887 kiloohm, R_n=2.56 kiloohm, PVVR=0.80,PVCR=2.4 by using (Eq.(1-5)) for double barrier RTD.

III. HYPOTHETICAL CONSIDERATION

By means of one dimension, timeless Schrodinger's equation can explain the performance of a single electron[10] [17];

$$-\frac{\eta^2}{2m^*}\frac{d^2}{dz^2}\psi(z)+V(z)\psi(z)=E(z)\psi(z) \quad (13)$$

By solving time independent differential Schrodinger's equation as a result of using NEGF and abridge using lorentnzian transform, we can acquire spatial difference of effective mass and Hamiltonian that integrate different pseudo-driven states contained by the devices;

$$-\frac{\eta^2}{2}\frac{\partial}{\partial z}\left[\frac{1}{m^*(z)}\frac{\partial}{\partial z}\psi(z)\right]+V(z)\psi(z)=E(z)\psi(z) \quad (14)$$

Schrodinger equation's solution needs function of wrapping estimates, i.e., both $\left(1/m^*\right)\left(\partial\psi(z)/\partial z\right)$ and $\psi(z)$, in order to ignore growing boundless and differentiating discontinuous functions, which are allowed by moving of electrons across the heterojunction and are continuous.

Well structure beneath contemplation for the multiple quantum are:

$$\kappa_2=\frac{\sqrt{2m_W^*E}}{\eta} \quad (15)$$

&

$$\kappa_1=\frac{\sqrt{2m_b^*(V-E)}}{\eta} \quad (16)$$

where wave vectors are k1 and k2 and Schrodinger equation's solution gives the eigenenergy of the structure of the device for unlike regions when field of electron is not present.

Suppose, if wavefunction in areas of barrier and well are Psi_w and Psi_b, dukeconditions of ben-daniel are typed [17]:

$$\psi_w(z)\big|_{interface}=\psi_b(z)\big|_{interface} \quad (17)$$

$$\frac{1}{m_w^*}\frac{d\psi_w(z)}{dz}=\frac{1}{m_b^*}\frac{d\psi_b(z)}{dz} \quad (18)$$

Imposing equations(17) and(18) on(14), eigen states of the formation under contemplation are acheived.

Modified Schrodinger's equation in the barrier and well regions are-

$$-\frac{\eta^2}{2}\frac{\partial}{\partial z}\left[\frac{1}{m_w^*(z)}\frac{\partial}{\partial z}\psi(z)\right]+V_w(z)\psi(z)=E(z)\psi(z) \quad (19)$$

And

$$-\frac{\eta^2}{2}\frac{\partial}{\partial z}\left[\frac{1}{m_b^*(z)}\frac{\partial}{\partial z}\psi(z)\right]+V_b(z)\psi(z)=E(z)\psi(z) \quad (20)$$

where m_w* and m_b* are effective masses of well regions and barrier regions, while V_w and V_b are potentials. As the function of mole consumption of aluminium and Galium, effective mass of large band gap material is measured, which finds the band conduction disconnection. For calculating intention, it is taken into account because the potential barrier height is obtained, that is, Superlattice's composite band diagram. [17].

IV. CURRENT CALCULATION

Subsequent Tsu-Esaki formulation[11],[18-22], the current density flowing during the RTD structure has been assumed equal to:

$$J=\frac{em^*kT}{2\pi^2\eta^3}\int_0^\infty dET(E,V).\ln\left[\frac{1+e^{(E_F-E)/kT}}{1+e^{(E_r-E-eV)/kT}}\right] \quad (21)$$

In the above equation, effective mass is m* and T is the temperature and transmission coefficient is T(E,V). The Fermi Energy level is E_f in the contact, energy of the incoming bloch waves is E and the biasing potential is V.

Lorentzian function approximates the transmission factor for double squared barriers.[11] [23]:

$$T(E,V)=\frac{\left(\frac{\Gamma}{2}\right)^2}{\left[E-\left(E_r-\frac{eV}{2}\right)\right]^2+\left(\frac{\Gamma}{2}\right)^2} \quad (22)$$

where, Γ is width of the resonance. Breath barrier and halved reduction of volatge that decreases from the emitter to the center of the well and is supposed to be equal to this formula.The coefficient of transmission remain trivial except when E almost equals resonance for smaller Γ, that is;

$$E \cong E_r - eV/2 \quad (23)$$

Measurements illustrate that Γ is in sequence of 1 meV or fewer than even breaths of thin barriers[21],[24] that is very smaller than kT in ambient condition.Result of intigral current density is:

$$J_{RTD} = \frac{em^* kT\Gamma}{4\pi^2 \eta^3} \ln\left[\frac{1+e^{(E_F - E_r + eV/2)/kT}}{1+e^{(E_F - E_r - eV/2)/kT}}\right] \cdot \left[\frac{\pi}{2} + \tan^{-1}\left(\frac{E_r - \frac{eV}{2}}{\frac{\Gamma}{2}}\right)\right] \quad (24)$$

The total appoximation gives collector voltage drop[11]:

$$V_c = \varepsilon\varepsilon_0 F^2 / 2eN_d \quad (25)$$

Here N_d is the donor concentration and F is the electric field it written such as V/d, d is the thickness of the barriers.The total voltage can be reresentation as[11]:

$$V_t = V + V_c \quad (26)$$

V. Simulated Results: Hartree Assumptions

Quantum Charge Density is calculated for central and relaxation areas of Hartree approximation. With same fermi level in relaxation area, distribution of carrier is presumed on condition of equilibrium. But non-equilibrium Green's function is calculated by density of states. Only diagonal of this function is taken by us for the measurement of states. In the central area, every parameters are measured by NEGF. Semi classical charge has been used for region of flat band, because in this region from the quantum charge, semi-classical charge will not deviate greatly. Mathematical burden will be decreased by doing this.

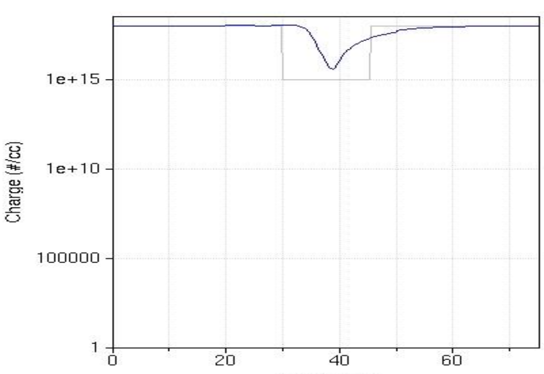

Figure 4 : Charge Density vs Length for Single Barrier RTD.

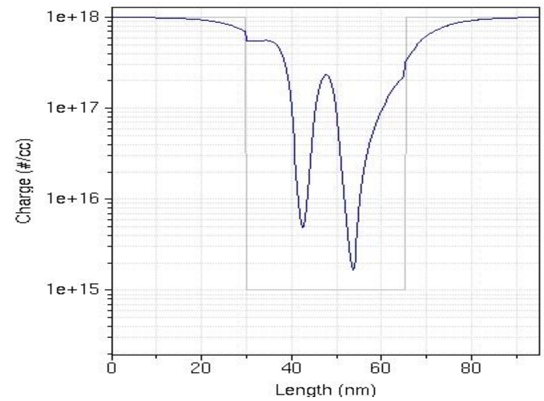

Figure 5 : Charge Density vs Length for Double Barrier RTD.

For single barrier Hartree model represents quantum charge density (Fig.4). Inside the barrier, quantum charge is not present, but this model provides quantum charge at the well portion, that is why, lower scattering and better confinement are found out inside the quantum well. Fig.5 represents double barrier Hartree model represents semiclassical charge density. Reservoir and contact portion are highly doped, i.e., higher scattering, as well lower confinement for both models.

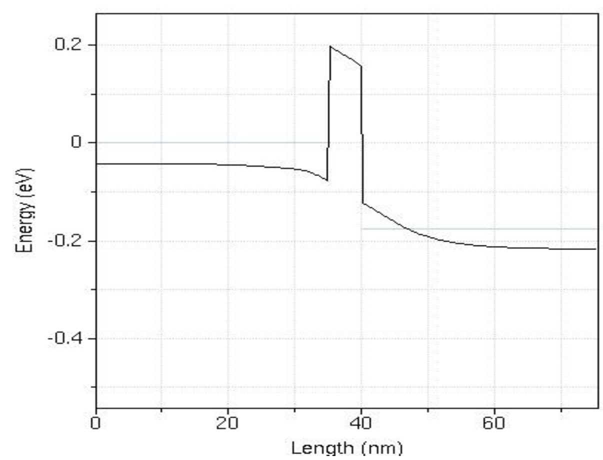

Figure 6 : Single Barrier RTD's Band Conduction.

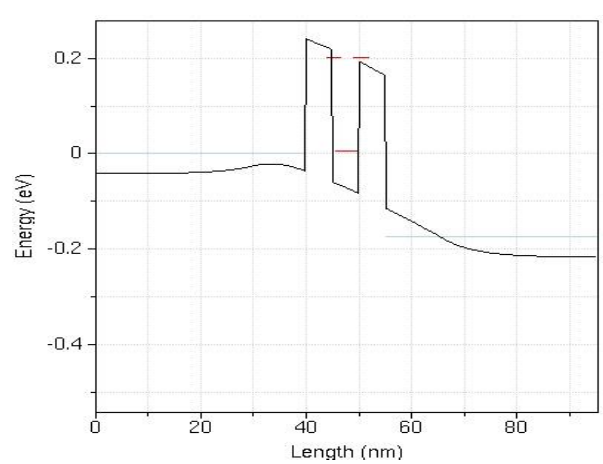

Figure 7 :Double Barrier RTD's Band Conduction.

By using effective mass model, the simulated results are found out for both single barrier and double barrier RTD. Figure 6 has shown the single barrier resonant tunneling diode's conduction band, while on the other hand, figure 7 has shown the double barrier resonant tunneling diode's conduction band. In the region of emitter notch, when a localized state lines up with the well state, the conduction peak of these RTDs occur.

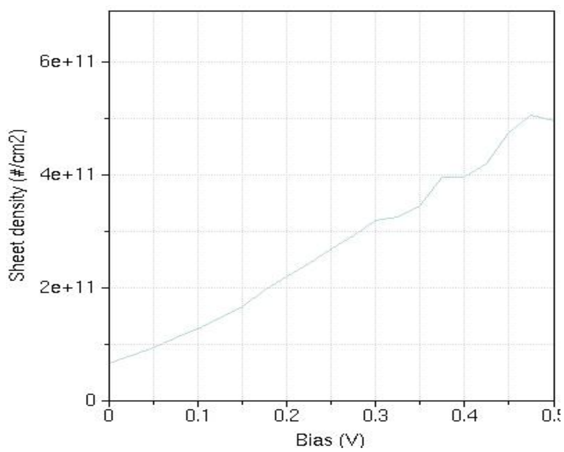

Figure 8 :Quantum Sheet Charge density for Single Barrier RTD

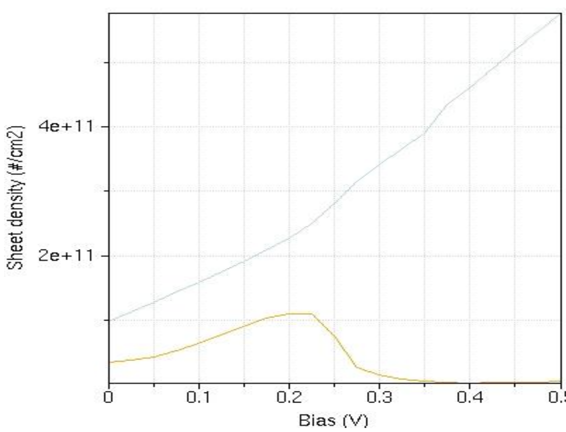

Figure 9 :Quantum Sheet Charge density for Double Barrier RTD.

Fig.8 showing quantum emitter sheet density for single barrier Hartree model and fig.9 represents quantum emitter sheet density as well as quantum devices density for double barrier Hartree model. Double barrier shows better sheet density compare to single barrier. Double barrier provides better performance because it has a quantum well inside the active medium, which is why more charge can accumulate in the well but single barrier does not have quantum well, that is why charge accumulation is not possible.

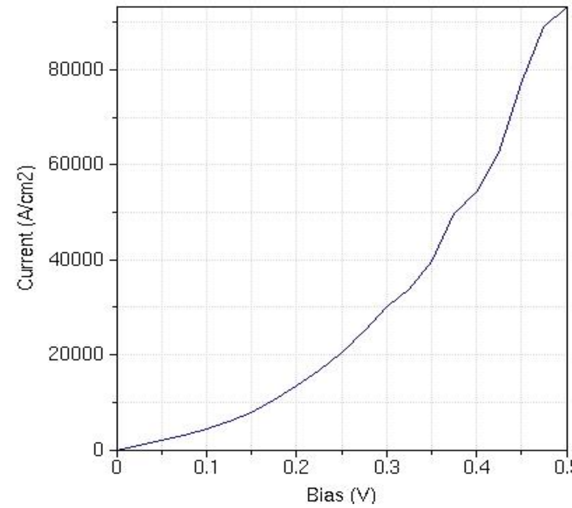

Figure 10 :I-V Charecteristics for Single Barrier RTD.

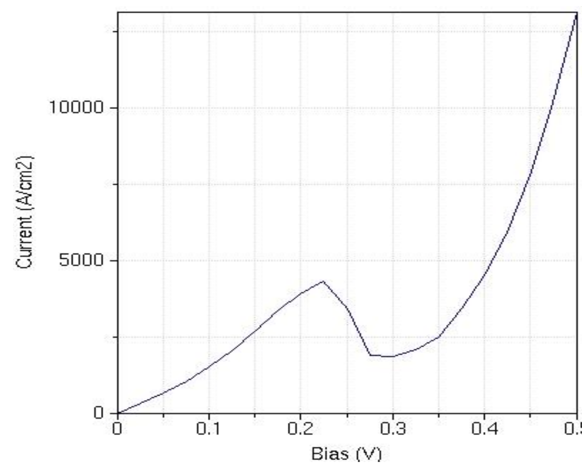

Figure 11 :I-V Charecteristics for Doublele Barrier RTD.

In a similar way, figure 10 and figure 11 have described the I-V characteristics of single barrier and double barrier RTD respectively. As the used structural design of RTDs are different, so I-V characteristics of them have been different. The forward I-V characteristics are approximately same as the simple p-n junction diode for the single barrier RTD. However, the current with respect to the voltage has risen until the peak point for the double barrier RTD. The device has shown negative resistance region until the valley point after the peak point gets achieved. The current has a dropping function of voltage for a particular range of voltage. Variable states of voltage-controlled logic can be supported in correspondence with valley and peak currents, which is why, this property holds a vital role in the prosecution of circuit.

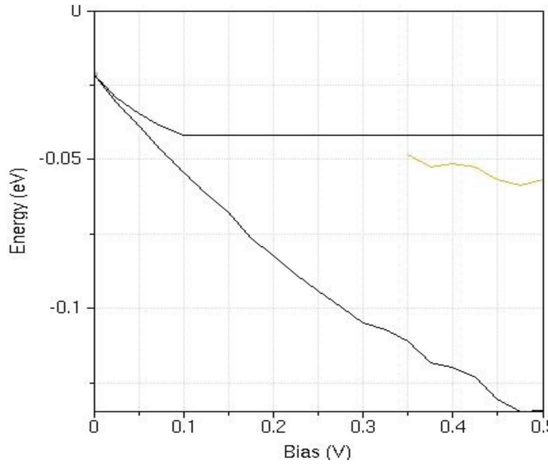

Figure 12 :Resonant Energy vs Applied Bias for one Barrier RTD.

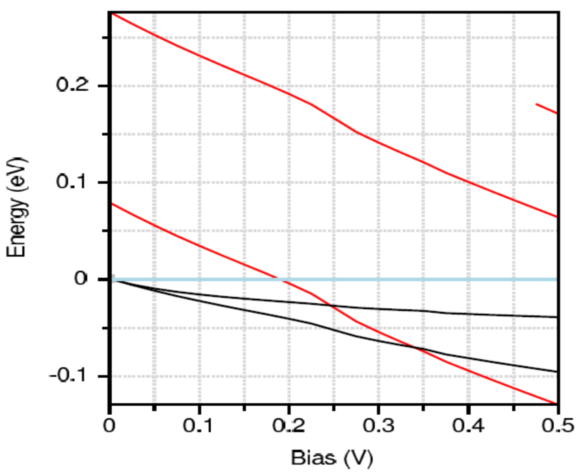

Figure 13 :Resonant Energy vs Applied Bias for two Barrier RTD.

Fig.12 and Fig.13 have explained the resonant energy vs applied voltage for single and double barrier RTDs respectively. When the wavelength of electron turns half-odd-integer multiple of width of the well, resonance happens at that moment. On the energy dispersion relationship, the energy corresponding to this wavelength support the locations of resonance. The dispersion for a given value of k is decreased by Band Non-Parabolicity. Thus, energy of resonance is remarkably overpredicted by roughly parabolic single band model. With discrete energy states, quantum well is acted by area between the two barriers for double barrier RTD. When the energy of electrons flow from the source and coincides with one of levels of the discrete energy in a well, then tunneling of resonance occurs through double barrier structure. By the help of a biased gate, the position of the boundary states can be modulated within the well.

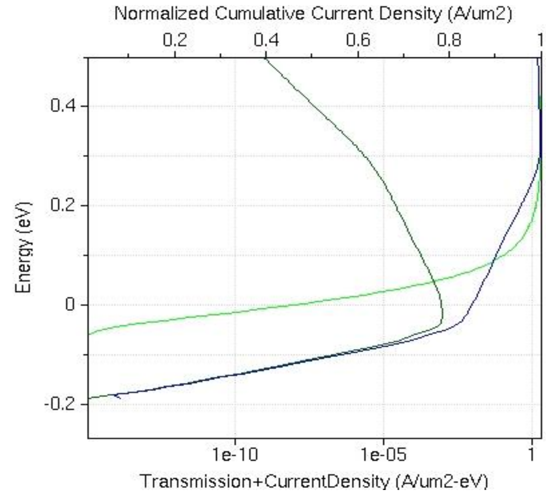

Figure 14 : Transmission Coefficient vs Energy vs Normalized Cummulative Current Density for Single barrier.

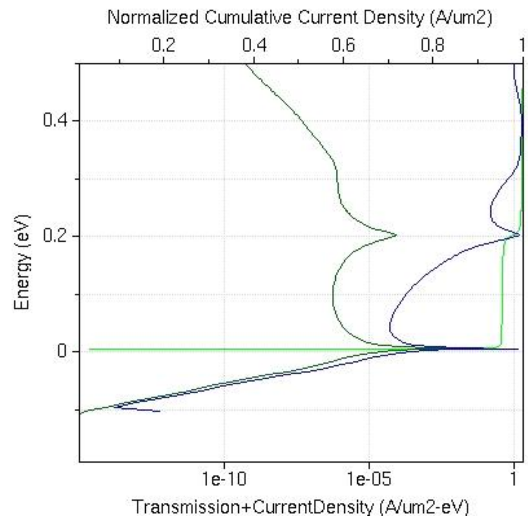

Figure 15 : Transmission Coefficient vs Energy vs Normalized Cummulative Current Density for Double Barrier.

Figure 14 and Figure 15 have shown the transmission coefficient vs energy vs normalized cumulative current density for single barrier resonant tunneling diode and double barrier resonant tunneling diode respectively. Penetration of electrons rely on the barrier width. The transmission coefficients are approximately equal to unity and depends on the barrier width and applied electric field, because the lower quantized energy level for both RTDs. The transmission coefficients for both are almost same as electric field and the barrier widths are equal for both simulated RTDs.

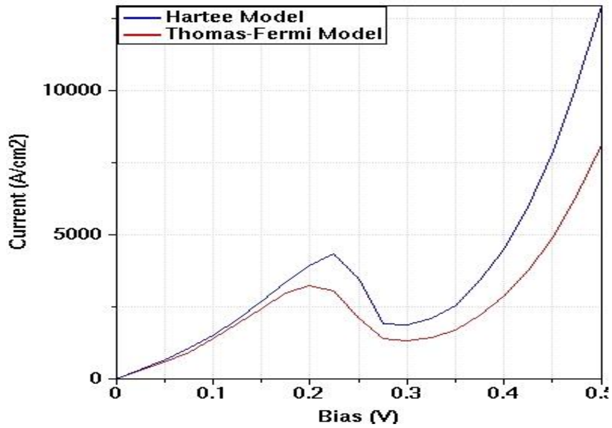

Figure 16:Combinational I-V Charecteristics plot.

Fig.16. repersents thomas and haretee model I-V characteristics for double barrier RTD. This I-V features shows comparison between thomas-fermi model and hartree model. Hartree provides better current density in the above figure**.**

The distance between the current peak and the valley current is represented by the Peak to Voltage Ratio (PVVR), which is an important figure of merit of RTD for both analog and digital uses. For choosing points of operation and optimizing margins of noise, a large PVVR is suitable specifically for memory and logic power functions. Moreover, switching applications need large PVVR because for reducing the off-state energy loss, a small amount of valley current is required. PVVR improves 21.21% by using hartree model. functions.

Comparisons Among RTD, Resonant Inter-Band TD and Esaki TD:

Table 2: Some comparisons among RTD, RTID and Esaki TD are shown below [25].

NDR Devices	Esaki TD	RTD	RITD
Design Flexibility	Material and Doping Limited	Very Good	Material Limited
Manufacture Ability	Fair	Good	Difficult
Speed Index	Medium (less than and equal to 100)	as high as 10^3	Medium (less than and equal to 100)
Peak Voltage	Small	Small to large	Small to Large
Operating Principle	Single barrier Tunneling	Resonant Tunneling	Resonant Tunneling
Carrier Transport	Bipolar	Unipolar	Bipolar

A. *Applications of RTD at Present Time:*

In today's time, both single and double barrier GaAs/AlGaAs RTDs can be used in oscillators when they are implemented in negative differential resistance region and in digital logic circuits when they are implemented in bi-stable condition.:

B. *Advantages of RTDs:*

1. Circuit speed is enhanced.
2. Power Consumption is reduced in a great amount.
3. Functionality is increased.

C. *Future Scope of RTDs:*

RTDs perhaps can replace the robust transistors as the grinder of integrated circuits within 2030s.

VI. Summary

After analysis of the simulated results, it can be declared that double barrier RTD is more promising than single barrier RTD, since, in the case of double barrier RTD,the current has reached at a peak value of 4800 A/cm2 at 0.25 Biased Volt, neatly the current has reached a value to almost 2400 A/cm2, which is the valley point, at 0.275 biased Volt and then has increased uup to12,500 A/cm2 at 0.5 biased Volt, whereas, in the case of single barrier RTD, the current has kept on increasing up to 10,000 A/cm2 at 0.5 biased Volt, without reaching any peak point and valley point values at specific biased voltages. It can also be seen that the model of Thomas-Fermi performs better than Hartree model considering the fact of defining NDR. Nevertheless, the Hartree model proves a better performance for applications which need higher current density in digital world. After all these inspections, it can be clearly stated that the proposed model performs more efficiently than the model described in[12].

VII. Conclusion

Based on the simulation results we can come to the conclusion that for any applications, the Hartree model performs more accurately due to the property of having higher PVVR at positive differential resistance region in comparison to Thomas-Fermi.

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REFERENCES

[1] Olivier Pinaud," Transient simulations of a resonant tunneling diode" vol.92,15 August 2002, page no. 1987-1994.
[2] S. Datta, "Non-Equilibrium Green's Function (NEGF) Formalism: An elementary Introduction," *Proceedings of the International Electron Devices Meeting (IEDM)*, IEEE Press (2002).
[3] S. Datta, "Nanoscale Device Simulation: The Green's Function Method," Superlattices and Microstructures, *28*, 253-278 (2000).
[4] S. Datta, "Electrical resistance: an atomic view," *Nanotechnology*, **15**, S433-S451(2004).
[5] M. P. Anantram, M. S. Lundstrom and D. E. Nikonov, "Modeling of Nanoscale Devices," http://arxiv.org/abs/cond-mat/0610247v2 (2007).
[6] M. Paulsson, "Non-Equilibrium Green's Functions for Dummies: Introduction to the One Particle NEGF equations," arxiv.org cond-mat/0210519 (2002).
[7] E. Polizzi, and S. Datta, "Multidimensional Nanoscale device modeling: Finite Element Method applied to the Non-Equilibrium Green's Function formalism," *IEEENANO 2003. Third IEEE Conference on Nanotechnology*, 2, 40-43 (2003).
[8] A. P. Jauho, "Introduction to the Keldysh nonequilibrium Green function technique,"
[9] N. Mingo and Y. Liu, "Phonon Transport in Amorphous-Coated Nanowires: Atomistic Green Function Approach," *Phys. Rev. B*, 70, 249901, 2004.
[10] Arpan Deyasi, Gourab Kumar Ghosh, "Effect of Dimention & Material Composition on Transmission Coefficient and Tunneling Current of Double Quantum Barrier Structure with Band Nonparabolicity", Bonfring International Journal of Power Systems and Integrated Circuits, Vol. 2, No. 3, December 2012.
[11] J.N. Schulman, H. J. De Los Santos, D.H.Chow, "Physics-Based RTD Current-Voltage Equation",IEEE ELECTRON DEVICE LETTERS, VOL.17, NO.5, MAY 1996.
[12] Vivek Sharma, Raminder Preetpal Singh, "Nano Scale Simulation of GaAs based Resonant Tunneling Diode" IJECS Vol.2 Issue 12, page no.3580-3583, December,2013.
[13] Johnny Ling, "Resonant Tunneling Diodes: Theory of Operation and Applications", page no.14627-14629,
[14] Madhukar Reddy, "Schottky-collector Resonant Tunnel Diodes for Sub-Millimeter-Wave Applications January"8,p6,1997
[15] http://www.ece.ucsb.edu/Faculty/rodwell/Downloads/theses/madhu_thesis.pdf (1997)
[16] R. Kosik, "Resonant Tunneling Diode Structure"
[17] http://www.iue.tuwien.ac.at/phd/kosik/node64.html
[18] P.Mazumder, S.Kulkarni, M. Bhattacharya, J.Ping Sun, and G.I. Haddad, "Digital Circuit Applications of Resonant Tunneling Divices"Proceeding of the IEEE, vol.86, no. 4, April 1998.
[19] A.Deyasi, S.Bhattacharyya,"Composite Effect of BenDaniel Duke Boundary Condition and Material Composition on Eigenenergy of Multiple Quantum Well Structure",International Journal of Soft Computing and Engineering(IJSCE) ISSN:2231-2307, Vol-1,Issue-4, September 2011.
[20] Charles E,. Chang, Peter M. Asbeck, Keh-Chung Wang, Elliott R. Brown, "Analysis of Heterojunction Bipolar Transistor/Resonant Tunneling Diode Logic for Low-Power and High-speed Digital Applications" IEEE Transactions on Electron Devices. Vol. 40. No. 4. April 1993, page 685-690.
[21] R. Tsu, L. Esaki, "Tunneling in a finite superlattice" Appl. Physics Letters, Vol. 22, pp. 562-564 (1973).
[22] Jian Ping Sun, George I. Haddad, Pinaki Mazumder, and Joel N. Schulman, "Resonant Tunneling Diodes: Models and Properties," Proceedings of the IEEE, vol. 86, p.641, April 1998.
[23] R. C. Bowen, G. Klimeck, R. Lake, W. R. Frensley and T. Moise, "Quantitative Simulation of a Resonant Tunneling Diode," *Journal of Applied Physiss*, vol. **81**, no.7,1996.
[24] Yan Z X, Deen M J. "New RTD large-signal DC model suitable for PSPICE[J]. IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems", 14(2):167-172,1995.
[25] D.K. Ferry, S.M. Goodnick "Transport in nanostructures" Cambridge studies in semiconductors physics and microelectronics engineering 2005.
[26] D. H. Chow, J.N.Schulman, E. Ozbay, and D.M. Bloom,"1.7-ps, microwave integrated-circuit-compatible InAs/AlSb resonant tunneling diode," Appl. Phys. Lett., vol.61, pp.1685-1687,1992(see Table I)
[27] Jian Ping Sun, P. Mazumder,Joel N schulman, "Resonant Tunneling Diodes: Models and Properties", IEEE Xplore May 1998.
[28] E. H. Miller, "A note on reflector arrays," *IEEE Trans. Antennas Propagat.*, to be published.

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