High Speed Resonant Tunneling Diode Based on GaN & GaAs: A Modeling & Simulation Approach

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Abstract

Double barrier Quantum well structure has been considered to model the Resonant Tunneling Diode (RTD) in terms of structural parameters to compute the electrical transmission characteristics. The transmission matrix for a RTD structure having any arbitrary barrier has been developed to simulate the resonant tunneling current with an applied voltage across GaAs and GaN based devices. The RTD structures have been extended as Resonant Tunneling Transistor (RTT) by introducing an additional optical control over the base quantum well. A significant tunneling improvement has been reported in case of optically activated RTT structures.

Keywords: RTD, Barrier, Laser, Double Barrier Quantum Well (DBQW), Refractive Index, Bandgap, Tunneling Current.

1. Introduction:

Quantum effect devices (QED) are based on quantum mechanical tunneling for controlled carrier transport through multi layer semiconductor structures when sub-band energies of adjacent quantum well coincides [1-3]. A smaller parasitic and compatibility of integration of such resonant structures with CMOS technology, has attracted theoretical and experimental researchers to develop appropriate models and application circuits based on Resonant Tunneling Diode (RTD) application in quantum electronics and optoelectronic sub-systems[4-5]. The RTD is perhaps the most promising candidate for digital circuit applications due to its negative differential resistance (NDR) characteristic, structural simplicity, ease of fabrication, inherent high speed, flexible design freedom, and versatile circuit functionality [6-8].

Fast speeds, low noise, reduced parasitic capacitances and high data rate have been reported in Transmitter module of GaAs HBTs [9] for Gigabit applications. Similar characteristics can be modeled using RTD structure, exploiting the tunneling current for say GaAs/GaAlAs employing SPICE [10]. These investigations have mainly focused on GaAs based materials and are modeled under numerical approximations like Breit-Wigner formula [11].

In this present work, a general model has been developed to model tunneling behavior of RTD using Transmission Matrix [12]. Any arbitrary potential can be discritised in small steps where tunneling can be approximated using transmission matrix concept. All these transmission probabilities are multiplied to obtain the tunneling co-efficient for the entire barrier. The analysis has been applied to two promising material GaAs and GaN based RTD structures. The details of this are given in the section on simulation and results. I-V characteristics for GAN and GaAs are simulated using the concept mentioned above and an approach to increase the peaks current in these I-V graphs is the main focus of our work.

Apart from studying the tunneling as an electrical phenomenon [13], we have investigated how light of different energies affect the tunneling process [14] in the two compound semiconductor materials chosen. Tunneling Current variation with different energies of barriers, barrier heights and electron energies has been studied. The change in refractive index of a semiconductor on interaction with photon is exploited to derive the relation between the band gap of a semiconductor and incident light [15-17]. A Bandgap variation ultimately leads to re-alignment of quantum states hence impacting the tunneling mechanism. All these theoretical explanations have been verified through MATLAB simulations using the transmission matrix model developed in case of GaAs and GaN based RTD structures.

2. Resonant Tunneling Diode (RTD) Structures and Model:

A RTD relies on quantum phenomenon such as tunneling and energy quantization to give an unusual current-voltage characteristic. For this quantum phenomenon to occur the dimensions of the active layer have to be on the order of the De-Broglie wavelength of electron. A typical RTD will have barriers of 2 nm thickness sandwiched with a lower Bandgap material of 5 nm thickness.

A Double Barrier Structure consisting of two Barriers and a quantum well structure is depicted in figure 1(a) for the unbiased case and figure 1(b) for the biased case.

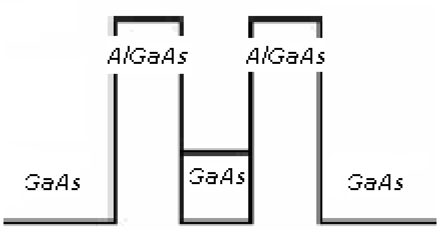

Fig 1a: Typical RTD structure with no Voltage Bias

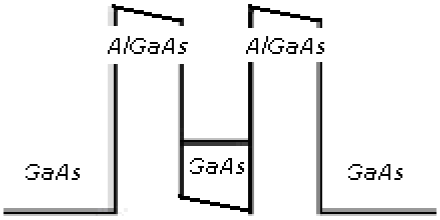

Fig 1b: Typical RTD structure with Voltage Bias

Evidently as the states in the quantum well align with the ones in the barrier, the quantum mechanical tunneling probability of electrons increases appreciably and determines the operating conditions and speed of such devices

High speed THz optical applications using compact solid state devices are possible through development of Integrated RTD Laser Diodes [18]. The front-end design of an optical receiver circuit can incorporate the RTD for High speed applications because of its insignificant parasitic as compared to conventional photodetectors used in the receivers. Further, in logical applications, the device can be biased with such a threshold potential that the overall structure can be made to go into tunneling mode to ease transmission for a logical high. For logic 0 it goes to switch off mode due to absence of resonant tunneling in the device and causing high switching speed. In Oscillator Circuits consisting of R, L, C and RTD, the Negative Differential Resistance (NDR) exhibited by RTDs can be used to compensate for unavoidable ohmic losses in such circuits [4]. RTD with a light controlled terminal can be used to increase tunneling current hence making it realizable for optoelectronics quantum devices.

The basic idea behind the simulation of the characteristics of a Resonant Tunneling Diode (RTD) is *transmission matrix*. Given any barrier height we have first found out what is the co-efficient of transmission across the barrier through quantum mechanical tunneling as the particle energy here we are dealing with is lesser than the energy of the potential barrier.

The transmission co-efficient across any arbitrary potential, as shown in figure 3, has been computed based on the known potentials.

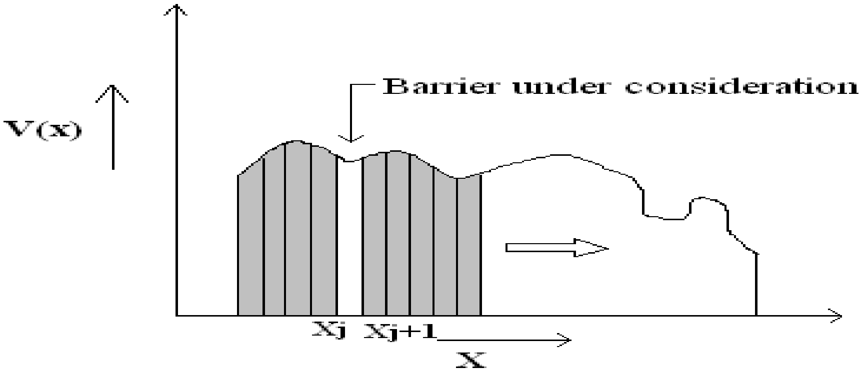

Fig 2: Discretization of the arbitrary potential barrier

Eigen functions can be found by discretizing the potential in small interval size and writing the wave vectors (kj) for respective barrier as given below

$$kj = (2mE - eVj)^{0.5} / (h/2\pi) \qquad (1)$$

where m is the effective mass of the electron, E is the energy of the incident electron, Vj is the applied potential across the barrier and h is the Plank's constant.

Now the coefficients of Eigen functions at the interface can be written as

$$\begin{bmatrix} Aj \\ Bj \end{bmatrix} = Pjstep \begin{bmatrix} Cj \\ Dj \end{bmatrix}$$

Where Pjstep can be written as : (2)

$$\mathrm{Pjstep} \quad = \quad 1/2 \begin{bmatrix} 1 + \mathrm{kj}+1/\mathrm{kj} & 1 - \mathrm{kj}+1/\mathrm{kj} \\ & \\ 1 - \mathrm{kj}+1/\mathrm{kj} & 1 - \mathrm{kj}+1/\mathrm{kj} \end{bmatrix}$$

Where A, B, C, D are the co-efficients as shown in the figure4.

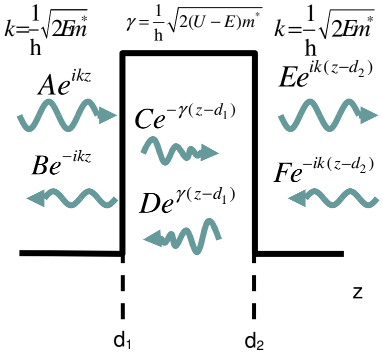

Fig 3: Details of transmission and reflection co-efficients of a barrier.

Obviously boundary conditions yield

$$\begin{bmatrix} A \\ B \end{bmatrix} = \frac{1}{2} \begin{bmatrix} \left(1-\frac{\gamma}{ik}\right)e^{-ikd_1} & \left(1+\frac{\gamma}{ik}\right)e^{-ikd_1} \\ \left(1+\frac{\gamma}{ik}\right)e^{ikd_1} & \left(1-\frac{\gamma}{ik}\right)e^{ikd_1} \end{bmatrix} \begin{bmatrix} C \\ D \end{bmatrix} \tag{3}$$

The matrix representation for the second boundary can also be developed in the same procedure to relate coefficients C, D with E, F to provide an equation as

$$\begin{bmatrix} C \\ D \end{bmatrix} = \frac{1}{2} \begin{bmatrix} \left(1-\frac{ik}{\gamma}\right)e^{\gamma(d_2-d_1)} & \left(1+\frac{ik}{\gamma}\right)e^{\gamma(d_2-d_1)} \\ \left(1+\frac{ik}{\gamma}\right)e^{-\gamma(d_2-d_1)} & \left(1-\frac{ik}{\gamma}\right)e^{-\gamma(d_2-d_1)} \end{bmatrix} \begin{bmatrix} E \\ F \end{bmatrix} \tag{4}$$

Using this matrix formulation, the reflection and transmission from the boundaries can be generalized as:

$$\begin{bmatrix} a_l \\ b_l \end{bmatrix} = \overline{\overline{\boldsymbol{M}}}_{l,l+1} \begin{bmatrix} a_{l+1} \\ b_{l+1} \end{bmatrix} \tag{5}$$

$$\overline{\overline{\boldsymbol{M}}}_{l,l+1} = \frac{1}{2} \begin{bmatrix} \left(1+\frac{k_{l+1}}{k_l}\right)e^{-ik_l(d_{l+1}-d_l)} & \left(1-\frac{k_{l+1}}{k_l}\right)e^{-ik_l(d_{l+1}-d_l)} \\ \left(1-\frac{k_{l+1}}{k_l}\right)e^{ik_l(d_{l+1}-d_l)} & \left(1+\frac{k_{l+1}}{k_l}\right)e^{ik_l(d_{l+1}-d_l)} \end{bmatrix} \tag{6}$$

The wave functions within the barrier can be modeled using a diagonal matrix Pjfree taking care of the phase transformation and free propagation inside the barrier and can be expressed as:

$$\mathrm{Pjfree} = \begin{bmatrix} \exp(-ikjLj) & 0 \\ 0 & \exp(ikjLj) \end{bmatrix} \tag{7}$$

Hence, the complete relation between the wave function on one side to another side is given by propagation matrix of j^{th} barrier and that is given by **Pj = Pjstep*Pjfree**

Finally for n discrete steps $P_{complete}$ is written as

$$P = \prod_{j=1}^{j=N} Pj \tag{8}$$

This expression can be evaluated for the given structural parameters under different bias conditions and thus provides the transmission probability across the device for an arbitrary potential barrier. The present simulation has taken a large number of discrete step functions to emulate the band bending of the barrier in case of applied potential.

3. Device Characterization and Discussion:

MATLAB simulations are performed to study the behavior of RTD structure based on GaAs/AlGaAs and GaN/AlGaN to estimate the transmission co-efficient through asymmetric double barrier at fixed voltage bias**.** Figure 4 shows the structural cross section and transmission characteristics for the considered structure.

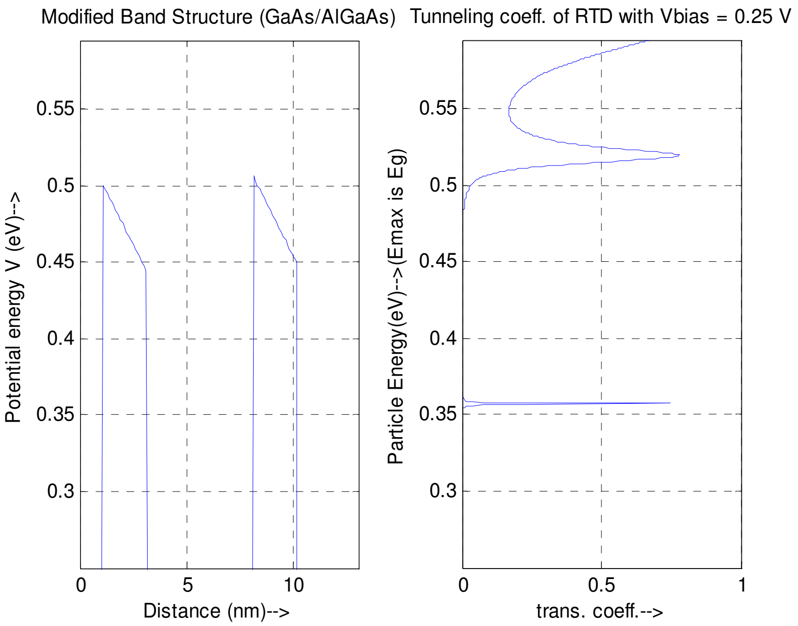

Fig 4: Tunneling Characteristic for a RTD with fixed voltage bias

The graph between tunneling current and. the voltage bias allows us to find the bias voltage at which resonant tunneling current peaks for the RTD device. The structural parameters considered for the simulation for the RTD structure based on GaAs/AlGaAs (shown in figure 1a) are: first barrier ($Al_{.4}GaAs_{.6}$ having Eg as 1.93 eV) width = 2 nm, height = 0.5eV; second barrier ($Al_{.4}GaAs_{.6}$ having Eg as 2.13 eV) width=2nm, height =0.7eV; Width of the well (GaAs having Eg 1.43 eV) in between =5nm. Under the assumption of a fixed current of 1 µA in the emitter side of the device The I-V characteristic has been simulated and presented in the figure 5.

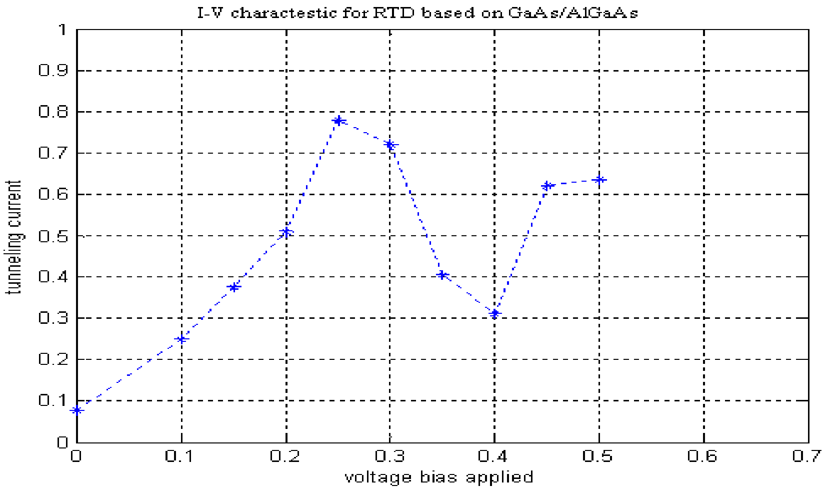

Fig 5: I-V Characteristic for RTD based on GaAs/AlGaAs

The I-V characteristics obtained is in close proximity to the experimentally reported results in [7]. The above figure clearly shows that peak tunneling current (0.78μA) occurs at voltage bias of 0.25V and valley current (0.31μA) at a voltage bias of 0.4V. Obviously, the I-V characteristic graph shows a NDR region to make it suitable for switching and oscillating circuits. The slope of NDR region is calculated as [(V_{peak}-V_{valley})/ (I_{peak}-I_{valley})] and comes out to be -0.319 for the considered typical structural parameters. The simulation has been extended for another promising material like GaN, to evaluate its suitability in quantum tunneling device applications and to establish its application in optoelectronics device design.

The I-V characteristics for GaN/AlGaN RTD structure have been simulated and the graph is reported in the figure 6. The simulation parameters are: first barrier ($Al_{.35}Ga_{.65}N$ having Eg as 4.194 eV) width = 2 nm, height = 0.694eV; second barrier ($Al_{.5}Ga_{.5}N$ having Eg as 4.6 eV) width=2nm, height =1.1eV; Width of the well (GaN having Eg 3.5 eV) in between =5nm.

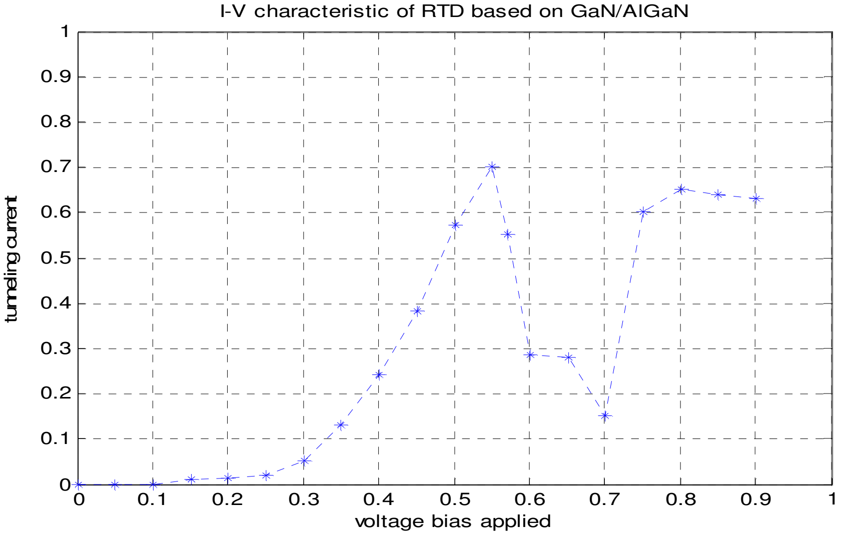

Fig 6: I-V Characteristic for RTD based on GaN/AlGaN

The I-V characteristics obtained is qualitatively similar to the case of GaAs based structure but with an quantitative difference. The above figure clearly shows that peak tunneling current (0.7μA) occurs at voltage bias of 0.55V and valley current (0.15μA) at a voltage bias of 0.7V and shows a NDR of -0.272. This characteristics show a scope to manipulate the peak tunneling current and the NDR value for the structures by the enhancement of the tunneling current.

4. Enhancement in Resonant Tunneling: Proposed Method

The present investigation proposes optical enhancement of tunneling current using laser light shone on the quantum well of the RTD structure. This can be viewed as Resonant Tunneling Transistor (RTT) with the base (quantum well) being controlled optically. The physics under lying the phenomena is generation of excess carrier through optical means and alteration of the optical density of the medium by the laser light. There are a few circumstances, where a normally non-transparent medium can be made transparent through coherent interaction with laser light of particular frequencies, which have been extensively studied in atomic and molecular systems [14]. Due to the laser-matter interaction there is a laser induced change in the material properties. It has been reported that the refractive index varies quite dramatically as the energy of the incident photon changes [15]. Change in refractive index in tern changes the effective band gap of that material [16-17]. The lowering of band gap energy implies increase in the density of states in the well of RTT, in other words it brings quantum energy states of that semiconductor material more close to each other. This ultimately increases the probability of resonant tunneling. This is because; more closely spaced quantum states in the well have higher probability of being aligned with the energy states of the emitter and collector sides. This enhancement in resonant tunneling current was expected theoretically and the same has also been verified through the simulations.

The change in refractive index of a material with photon energy is well established in literature. So the values of refractive indices for different photon energy, for GaAs and GaN are used in the simulations. From [16-17] two mathematical relations reported for Bandgap energy-Refractive Index relation are used. The relation for GaAs is determined using the Ravindra Formula and for GaN using the Moss Formula. This is because; Bandgap of GaAs falls in the region where Ravindra Relation gives results closest to the experimental values reported [15]. Similarly Moss relation is found to be best suit for GaN. These two relations are given below.

Ravindra Formula: $E_g n^4 = 108$ eV (8)
Moss Formula: $E_g n^4 = 95$ eV (9)

The simulation results and tabulations for the GaAs/AlGaAs RTT structure under considerations is shown below:

Table 1: Photon energy and their corresponding n values to give different tunneling currents

Photon Energy(eV)	Refractive Index (n)	Eg from (Ravindra Model)	Tunneling Current For bias 0.25V
0	3.3	1.35	.78
0.42	3.08	1.2	0..8476
.49	3.147	1.1	0.85
0.55	3.223	1	0.8625
0.62	3.3	0.9	0.8977
0.7	3.408	0.8	0.898
1.25	3.524	0.7	0.9085
1.3	3.546	0.6	0.9085
1.33	3.55	0.5	0.9085

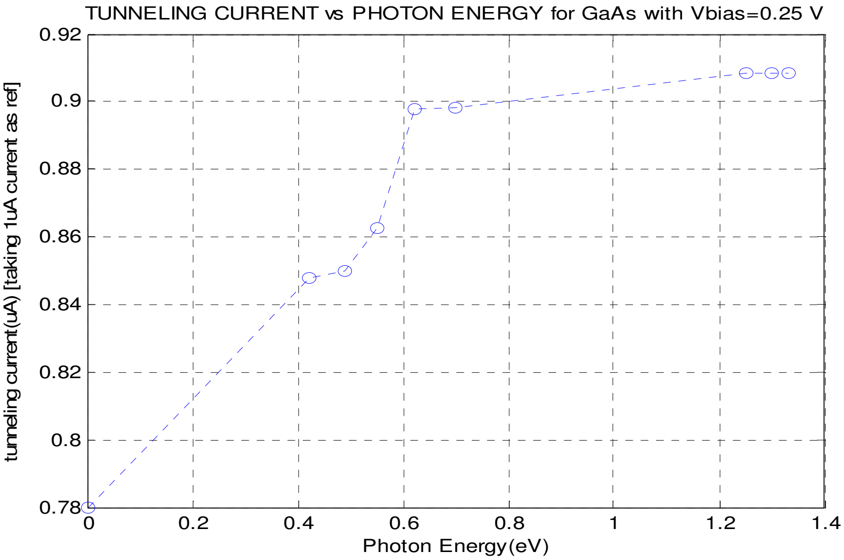

Fig 7: Tunneling current vs. Photon energy for GaAs/AlGaAs RTT

The above simulation is performed at voltage bias of 0.25V that gave maximum resonant tunneling current (figure 5). It is clear from the above graph that without any light shown on the well the tunneling current obtained is 0.78µA.We report that there can be an increase in resonant tunneling current upto 16.47% in the above system with light of different energies. For photon energies closer to the band gap of the material the tunneling current saturates.

The simulation results and tabulations for the GaN/AlGaN RTT structure under considerations is shown below:

Table 2: Photon energy and their corresponding n values to give different tunneling currents

Photon energy (hν)(eV)	Refractive Index(n)	Modified Band Gap Eg (eV)(Moss Relation)	Tunneling Co-efficient at 0.55 V Bias
0	2.28	3.5	0.7
1.0	2.33	3.48	0.7
1.5	2.35	3.46	0.7
1.6	2.364	3.445	0.7
1.7	2.371	3.43	0.7
1.8	2.378	3.38	0.705
1.9	2.385	3.345	0.705
2.0	2.39	3.34	0.7051
2.25	2.41	3.2	0.79
2.5	2.44	2.68	0.827
2.75	2.48	2.511	0.86
3	2.54	2.282	0.86
3.25	2.6	2.07	0.86

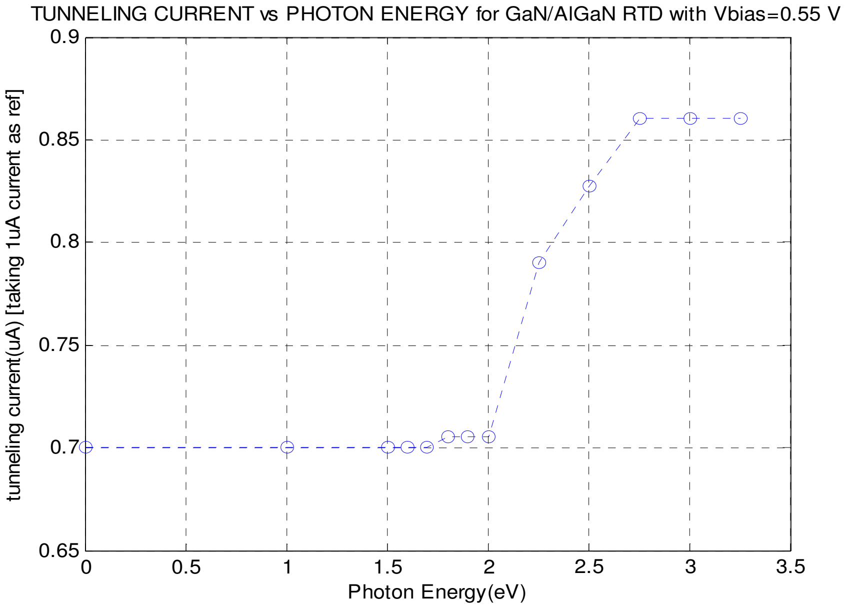

Fig 8: Tunneling current vs. Photon energy for GaN/AlGaN RTT

The above simulation is performed at voltage bias of 0.55V that gave maximum resonant tunneling current (figure 6). It is clear from the above graph that without any light shown on the well the tunneling current obtained is 0.7µA.We report that there can be an increase in resonant tunneling current upto 22.85% in the above system with light of different energies. GaN is a wide Bandgap semiconductor .Hence photon energies upto 2 eV have no influence on the tunneling current. The tunneling current increases sharply for photon energies ranging from 2-2.75 eV and after which the current saturates.

Conclusion:

Double barrier quantum well structures have been used to model the resonant tunneling devices. A simple transmission matrix has been developed to evaluate the quantum mechanical characteristics of the electron wave across the structure. The developed model has been used to simulate the resonant tunneling current with an applied voltage across GaAs and GaN based RTD structures. It is observed through simulations that the tunneling currents for these structures peak at 0.25V and 0.55V respectively. The present investigation reveals the NDR behavior for both the structures but the former with a higher value to confirm its suitability for oscillator applications. It is also observed that optical exposure in the well leads to a significant improvement in the tunneling behavior. It is observed that GaN based RTT shows nearly 22.85 % increase in the tunneling current as against a 16.47 % increase in the case of GaAs based RTT, establishing the superiority of GaN based quantum structures for optoelectronic applications.

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