Dependence of Peak Tunneling Current Density on Structural Parameters in Rectangular DQW Device

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Abstract: Peak of tunneling current density of double quantum well device is analytically computed for different structural parameters, material composition and applied bias. Energy propagation is considered along the direction of applied bias, and travelling wave is measured w.r.t input wave at each grid point inside the structure. Rectangular well geometry is considered for ease of simulation. Effective mass mismatch at hetero-interfaces are taken into account by considering BenDaniel Duke boundary condition. High peak value at specific conditions will help to work the device for resonant tunneling application, precisely for the fabrication of RTD and RTT.

Keywords: Tunnelling current density; peak current; structural parameters; double quantum well; applied bias.

1 INTRODUCTION

Theoretical and experimental research in nanoelectronics and nanophotonics have attracted workers in the last two decades due to its immense possibility in designing novel electronics [1, 2] and photonics [3, 4] devices for various applications. Owing to the confinement of carriers along the quantized dimensions, physical realization of quantum well, wire or dot becomes possible not only in theoretical aspect, but also in experimental field. Connection of these quantum devices with external world are made by tunneling mechanism, and output of this quantum mechanical phenomenon becomes measurable and non-negligible when resonant tunneling takes place. The likelihood that the electron will pass through the barrier is given by the transmission coefficient, and this type of finite potential barrier problem demonstrates the phenomenon of quantum tunneling. Therefore, for any quantum device, precise estimation of tunneling output becomes essential. Role of structural parameters [5] and material composition [6] plays a crucial role in this regard.

Among all the quantum devices, quantum well is the most suitable choice for theoretical and experimental researchers owing to ease of fabrication [7-8] and computation [9-10]. Physical properties of heterostructure devices can be estimated from the knowledge of quantum transport processes. To understand the electronic and optical properties of the nanostructures, computation of their eigenstates is very essential [11] along with density of states profile [12]. Current density is estimated from the knowledge of eigenenergy and DOS.

Wessel [13] showed that for computation of tunneling current, thermal probability should be estimated. Later, Song [14] proposed a transition layer model to compute the same for double quantum well system. This tunnelling current is minimized by Muhanna [15] for lasing application.

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Importance of structural parameters is also investigated [16] for LED design. In present paper, peak magnitude of tunneling current density is analytically investigated as a function of structural parameters and applied bias. Multiple peaks are obtained under suitable applied bias conditions. Result will play crucial role in determining the electrical behavior of resonant tunneling based devices.

2 MATHEMATICAL MODELING

For one-dimensional quantum confinement, time-independent Schrödinger equation is given by

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

where ζ(z) is the applied field along the direction of wave propagation. Here effective mass m* is inside the differentiation which indicates that it varies from grid point-to-point.

For the double barrier structure under consideration as shown in Fig, we consider the solutions to Schrödinger's equation within each region for E<V –

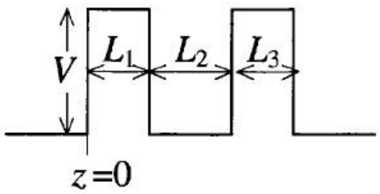

Fig. 1. Schematic picture of double quantum well.

$$\psi(z)=A\exp[i\kappa_1 z]+B\exp[-i\kappa_2 z]$$

for $z<I_1$ (2.1)

$$\psi(z)=C\,\mathrm{xp}[\kappa_1 z]+D\exp[-\kappa_2 z]$$

for $I_1<z<I_2$ (2.2)

$$\psi(z)=F\exp[i\kappa_1 z]+G\exp[-i\kappa_2 z]$$

for $I_2<z<I_3$ .. (2.3)

$$\psi(z)=H\exp[\kappa_1 z]+I\exp[-\kappa_2 z]$$

for $I_3<z<I_4$ (2.4)

$$\psi(z)=K\exp[i\kappa_1 z]+L\exp[-i\kappa_2 z]$$

for $I_4<z<I_5$ (2.5)

where κ_1 and κ_2 are defined as

$$\kappa_1=\frac{\sqrt{2m_w^* E}}{\hbar} \quad (3.1)$$

$$\kappa_2=\frac{\sqrt{2m_b^*(V-E)}}{\hbar} \quad (3.2)$$

The positions of interfaces have been labelled I_1, I_2, I_3 and I_4 respectively. Using standard BenDaniel-Duke boundary conditions at each interface, and introducing transfer matrix technique,

$$\begin{pmatrix}A\\B\end{pmatrix}=M_1^{-1}M_2M_3^{-1}M_4M_5^{-1}M_6M_7^{-1}M_8\begin{pmatrix}K\\L\end{pmatrix} \quad (4)$$

We assume that there are no further heterojunctions to the right of the structure, so that no further reflections can occur and wave function beyond the structure can only have a travelling wave component moving to the right, i.e. the coefficient *L* must be zero. Thus equation (4) can be modified as:

$$\begin{pmatrix}A\\B\end{pmatrix}=M\begin{pmatrix}K\\0\end{pmatrix} \quad (5)$$

So transmission coefficient can be given by-

$$T(E)=\frac{KK^*}{AA^*}=\frac{1}{M_{11}^*M_{11}} \quad (6)$$

Thermal equilibrium probability is calculated assuming the physical probable range of wave vector as

$$P=\frac{dk}{2\pi\hbar^2\ln[1+\exp(E_F-\hbar^2(n_k-1)dk+k_{\min})^2]} \quad (7)$$

where n_k denotes the range of '*k*' values, k is the minimum value of wavevector, E_F is the Fermi energy. Tunneling current density is theoretically defined as the probability of finding the electron in a region of space due to the flow of wavevector, either form left or right of the structure. This is defined as

$$J_z=\frac{\hbar}{2m^*}\left[\psi'\frac{\partial\psi}{\partial z}-\psi\frac{\partial\psi'}{\partial z}\right] \quad (8)$$

In practice, it is calculated from the knowledge of Fermi function as

$$J_z = \frac{2q}{h}\int_{U_L}^{\infty}[f(E,\mu_L) - f(E,\mu_R)]T(E)dE \quad (9)$$

3 RESULTS AND DISCUSSION

Based on the mathematical formulation as mentioned in section II of this paper, peak tunneling current density is analytically calculated and plotted as function of various structural parameters, material composition and applied bias.

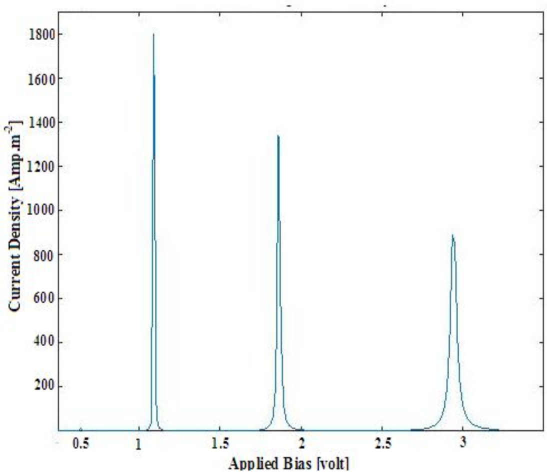

Fig. 2. Current density profile with applied bias with multiple peaks.

Fig 2 shows the occurrence of multiple peaks in current density profile with applied bias. It may be noted that with increase of bias, height of the peak decreases. Also variation of current is discrete which speaks about the choice of external bias for obtaining requisite current. Since with higher applied field, quantum confinement decreases, hence magnitude of current also decreases.

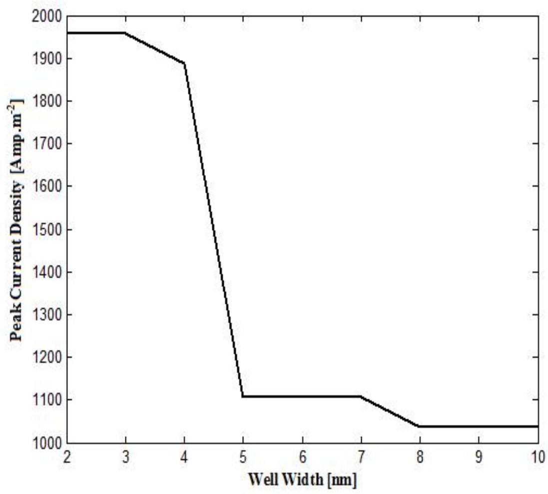

Fig. 3. Peak tunnelling current density as a function of well width of DQW structure.

Fig 3 shows that peak of tunneling current density varies with well width of the rectangular DQW device. From the plot, it is seen that peak magnitude of current density decreases with increasing well dimension. This is due to the fact that with increase of well dimension, quantum confinement decreases, which reduces the tunneling probability. The variation is more significant for lower well layer width, but almost becomes constant when layer dimension becomes large.

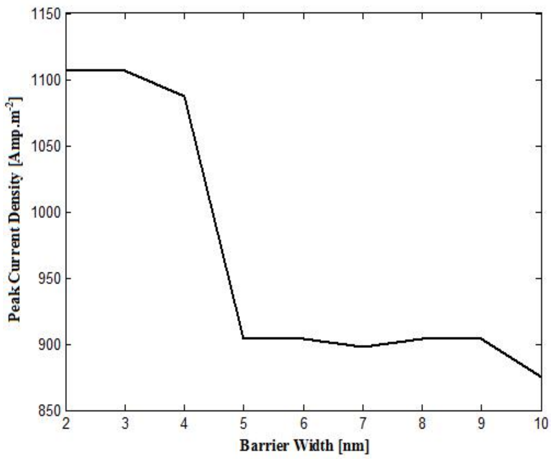

Fig. 4. Peak tunnelling current density as a function of barrier width of DQW structure.

Fig 4 shows the peak density variation w.r.t barrier width. Similar nature as Fig 3 is observed in this case also. But the noticeable fact is that the rate of decrement for well width variation is much higher than the barrier layer change. Thus it may be concluded that tuning of well dimension has more effect on tunneling mechanism in double quantum well structure.

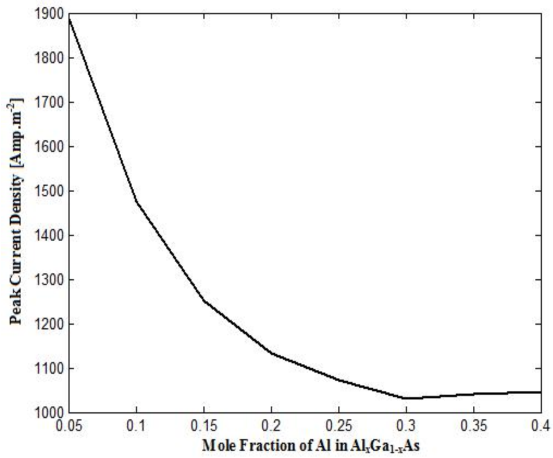

Fig. 5. Peak tunnelling current density as a function of material composition of DQW structure.

Fig 5 shows the tunneling current variation as function of Al mole composition. It is seen from the plot with increase of Al percentage in AlGaAs, tunneling current monotonically decreases, and the nature remains same upto x=0.3. With further increase of *x*, current starts to grow. This is because higher Al mole fraction enhances the quantum confinement, thus current decreases. This attains minimum when barrier material composition becomes $Al_{0.3}Ga_{0.7}As$. Further increment of *x* again aligned the energy levels of adjacent wells, which enhances the tunneling current.

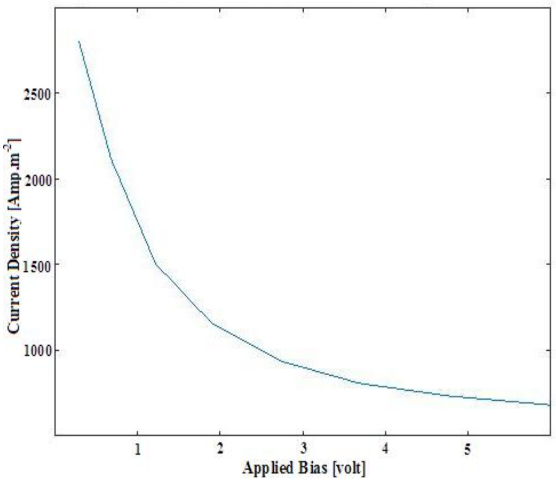

Fig. 6. Peak current density with applied bias.

By keeping structural parameters constant, peak current density can externally be tuned by changing applied voltage. This is represented in Fig 6. It is observed from the plot that with lower bias values, tunneling current decreases rapidly, which speaks about non-overlapping of energy states between adjacent quantum wells. At higher voltage, band of the system is so bend that complete overlapping is happened, as a result of which tunneling current decreases slowly.

4 CONCLUSIONS

Effect of well width, barrier width, material composition and applied bias are graphically represented on peak magnitude of tunneling current density in a double quantum well device with rectangular well geometry. Maximum tunneling current speaks about its possible application in resonant tunneling devices.

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