TUNNELING EFFECT IN DOUBLE BARRIER NITRIDE (AlGaN/GaN) HETEROSTRUCTURES AT VERY LOW TEMPERATURE

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ABSTRACT: *Tunneling effect has been studied in double barrier (AlGaN/GaN) heterostructure and tunneling probability has been found out for electrons to tunnel across the barrier. Tunneling probability changes as the temperature changes. Here tunneling probability has been taken at very low temperature (77K). The potential distribution has been shown in the heterostructure. Tunneling current for double barrier nitride (AlGaN/GaN) heterostructure has been traced and revealed figure of merit at 77K equals about 15.*

Keywords: AlGaN/GaN, Heterostructures, Tunneling Effect

INTRODUCTION

The nitride based devices are most suitable for high power, high frequency, high temperature and also essential radiation hardness. The driving force for nitride semiconductor is due to device applications for emitters and detectors in the visible and ultraviolet (UV) portions of the optical spectrum and high-power amplifiers [1, 2]. It is possible to make high electron mobility transistors (HEMTs) with GaN because it has large band gap and thermal properties. In this paper, the potential distribution and the tunneling current has been determined by taking nitride (AlGaN/GaN) double barrier heterostructure.

1. DEVICE STRUCTURE

For thick barrier, both Newtonian and Quantum mechanics say electrons cannot cross the barrier. It can only pass the barrier if it has more energy than the barrier height. For thin barrier, Newtonian mechanics still says that the electrons cannot cross the barrier. However, Quantum mechanics says that the electron wave nature will allow it to tunnel through the barrier. During the tunneling the particle energy does not change. The structure consisted of two barrier layers and two well layers. The well layer is inserted between two barrier layers. The device also resists the radiation damaging effects of nuclear radiation. Because it is less dependent on the structural perfection of its crystal than is transistor. It is much less affected by the damage that radiation can do to such crystals structures. It is also little affected by the environmental conditions. This structure based tunnel diode shows great promise as an oscillator and high-frequency threshold (trigger) device since it can be operated at frequencies far greater than the tetrode would, well into the microwave bands.

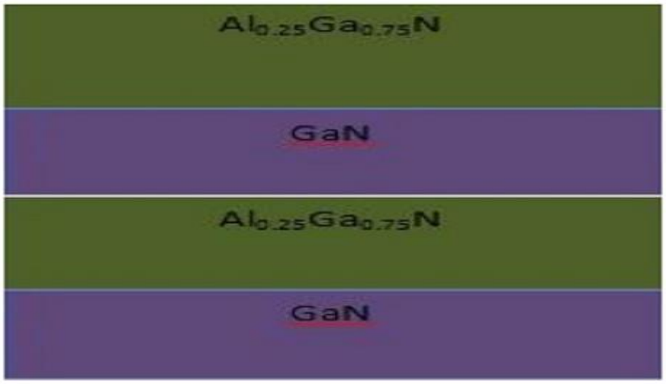

Fig. 1: Nitride double barrier heterostructure showing composition of layers

Applications for these nitride (AlGaN/GaN) double barrier heterostructure based tunnel diodes included local oscillators for UHF television tuners, trigger circuits in oscilloscopes, high speed counter circuits, and very fast rise time pulse generator circuits [1, 3].

2. THE POTENTIAL DISTRIBUTION IN NITRIDE DOUBLE BARRIER HETEROSTRUCTURE

The distribution of potential in heterostructure changes with biasing voltage. The distribution of potential has been shown for various biasing voltage range. The double barrier quantum well structure acts as a fabry - Perot resonator [4-6]. An electron from one contact may tunnel through to the structure to the other contact if its energy is close to a quantized level. Therefore no current flows through the device so long as the lowest quantized level in the well E_0 is above the Fermi level E_F in the contact layer. However when a voltage V is applied between the two end contact layers, energy levels at one end are pushed up and those in the other end are pushed down by $|e|V/2$, with reference to the energy levels in the well if it is assumed that the barriers are identical and the voltage is distributed uniformly across the device. Consequently, when $E_f + |e|V/2$, is equal to E_0 as shown in Fig.5, current starts flowing and continues to flow till E_0 is less than $Ec + |e|V/2$, As E_0 falls below the conduction band edge of the contact layer for larger voltages, the current drops to zero. A current peak is therefore expected near $V = 2(E_0 - Ec)/|e|$, Similar peaks are also expected at higher voltages near the higher lying quantized levels. It is however, clear that the current in the device is produced basically by the tunneling of the electrons through the barriers.

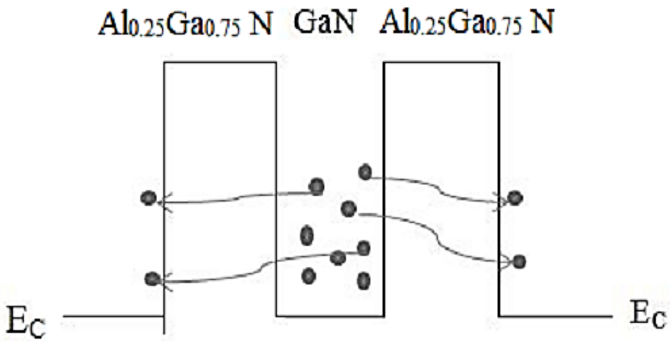

Fig. 2: Potential distribution in double barrier quantum well structure in absence of applied voltage (V)

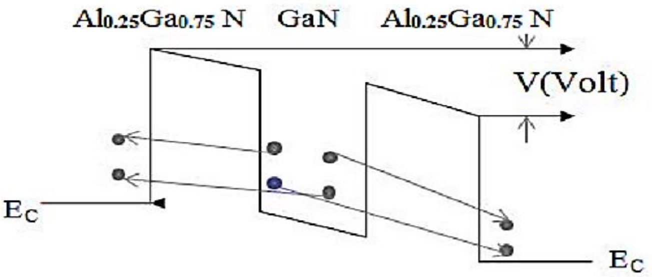

Fig. 3: Potential distribution in double barrier quantum well structure in presence of applied voltage (V)

Current in the device being produced by the tunneling of the electrons, the frequency and the speed limitation of the device is controlled by the tunneling time and the effective device capacitance. Since these two parameters are very small in this structure, the operating frequency and the switching speeds of the device can be expected to be much higher than that of other available devices.

3. TUNNELING CURRENT

When the applied voltage in the semiconductor is sufficiently high then a finite probability exists for interband quantum tunneling, i.e. direct transition of electrons from conduction band into valence band and vice versa. The tunneling probability (transmission coefficient) T can be found by solving Schrodinger wave equation and applying some boundary conditions [7-11].

For special case, when E the total energy of the particle is very much less than the potential barrier the boundary conditions are:

(1). Since the square of wave function $\psi(x)$ represents the probability density function, then for a single particle we must have that $\int_{-\infty}^{\infty}(I)\,dx = 1$, where $I = (\psi(x))^2$

(2). $\psi(x)$ must be finite, single-valued and continuous. $d\psi(x)/dx$ also must be finite, single-valued and continuous.

Now, the Tunneling probability

$$T = 16\left(\frac{E}{V_0}\right)\left(1-\frac{E}{V_0}\right)\exp(k_2 a) \qquad (1)$$

where $k_2 = \sqrt{4m\pi(V-E)/h}$.

Here E, V_0, m and a are total energy of particle, barrier height, electron mass and barrier width respectively. The total tunneling current can be calculated by summation of the current the current due to the electrons impinging on the barrier from its left (I_L) with that due to the electrons arriving from its right (I_R).

Here, $I_L = (2e)\int_0^{\infty}(q)\,dk$ where $q = f(\epsilon(k),\mu_L)v(k)T(k)/(2\pi)$, by changing the variable of integration

$$I_L = (2e)\int_{U_L}^{\infty}(q)\,dE \qquad (2)$$

where $q = f(E,\mu_L)T(E)/(h)$.

And

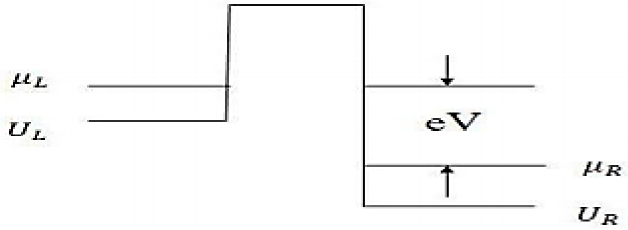

Fig. 4: Potential distribution in double barrier quantum well structure at very small applied voltage (V)

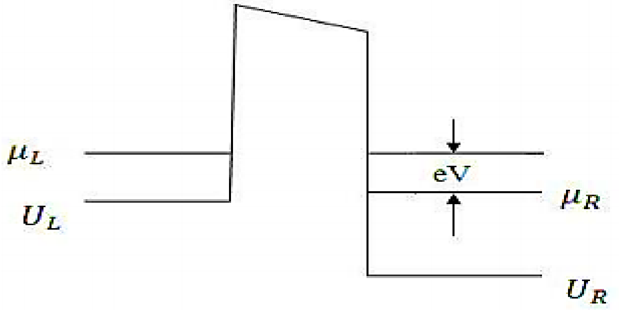

Fig. 5: Potential distribution in double barrier quantum well structure at small applied voltage (V)

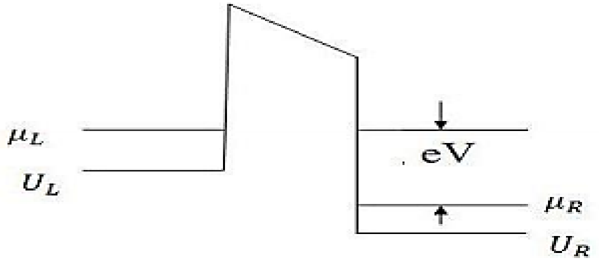

Fig. 6: Potential distribution in double barrier quantum well structure at very large applied voltage (V)

$$I_R = (2e)\int_{U_R}^{\infty}(z)\,dE \qquad (3)$$

where $z = f(E,\mu_R)T(E)/(h)$.

Now two equations give the net current

$$I = I_L + I_R = (2e)\int_{U_L}^{\infty}(q-z)\,dE \qquad (4)$$

Results from equation (4) are as follows:

(1). I = 0 when bias voltage V = 0 and$\mu_L = \mu_R$.

(2). If the bias is very small the difference in Fermi functions can be expanded to the lowest order in a Taylor series. Put $\mu_L = \mu + 1/2\ \mathrm{eV}$ and$\mu_R = \mu - 1/2\ \mathrm{eV}$ where μ is the Fermi level at the equilibrium.

$$f(E,\mu_L) - f(E,\mu_R) \approx eVf(E,\mu)/\mu = -eVdf(E,\mu)/dE \qquad (5)$$

Now from equation (4)

$$I = 2Ve^2\int_{U_L}^{\infty}(-df/dE)dE \qquad (6)$$

The bias voltage (V) in equation (6) is directly proportional to the bias voltage thus Ohm's law holds for small bias voltage. For very low temperature $-df/dE = \delta(E-\mu)$ then equation (6) reduces to

$$I = (2Ve^2)/hT(\mu) \qquad (7)$$

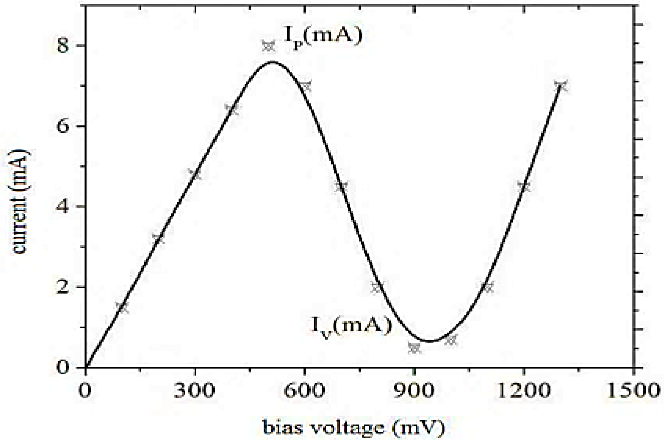

Fig. 7: Plot of tunneling current in double barrier quantum well structure at applied bias voltage (mV)

(3). When bias is large in Fig.6, all incoming states on the right hand side may be below the left hand side plateau U_L and there make no contribution to the current. In this case the occupation function f(E, $4\mu_R$) can be dropped from equation (4).

$$I_L = (2e)\int_{U_L}^{\infty}(q)\,dE \tag{8}$$

Where $q = f(E,\mu_L)T(E)/(h)$. At very low temperature, Fermi occupation function can be approximated by step functions. Only electrons with energies between μ_L and μ_R contribute to the current

$$I = (2e/h)\int_{U_R}^{U} T(E)\,dE \tag{9}$$

For this plot, the figure of merit at near to 77K is $I_P/I_V = 15$. Here I_P and I_V are the peak current and valley current respectively.

4. CONCLUSION

Tunneling effect in nitride based heterostructure has been studied. It was studied at 77K and computations were done with parameters – Eg($Al_{0.25}Ga_{0.75}N$): Energy band gap of $Al_{0.25}Ga_{0.75}N$, Eg(GaN): Energy band gap of GaN, ϵ(x=0.25): Dielectric constant, m_0(electron mass) and ΔE_C(conduction band discontinuity) respectively. Here (x = 0.25) is the Al mole fraction. Also the potential distribution in nitride heterostructure has been displayed for various biasing voltage.

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