Int. J. Nanoelectronics and Materials **6** (2013) 129-137

Effect of device parameters on transmission coefficient of $Al_{0.2}Ga_{0.8}N$/GaN Resonant Tunneling Diode grown on silicon substrate

Subhra Chowdhury*[1], Dhrubes Biswas[2]

[1]*Advanced Technology Development Center, Indian Institute of Technology Kharagpur, Kharagpur-721302, West Bengal, India.*
[2]*Electronics and Electrical Communication Engineering, Indian Institute of Technology Kharagpur, Kharagpur-721302, West Bengal, India.*

Received 7 June 2012; Revised 14 Aug. 2012; Accepted 24 Aug. 2012

Abstract

AlGaN/GaN Resonant Tunneling Diodes (RTD) have increasingly become important, since these are ideally suited for high power, high frequency performance and capable of providing negative differential resistance at room temperature. Transmission coefficient (Tc) is an important factor to determine the negative differential resistance (NDR) and peak-to-valley ratio of RTD. An analytical model is developed here to predict the variation of Tc of AlGaN/GaN RTD structure with life time of carrier which is affected by different factors such as doping concentration, temperature and dislocation density in the film grown on substrate of different material. A comparative study of performance of RTD in terms of mobility of carrier in GaN grown on silicon substrate is also studied in this analysis.

Keywords: AlGaN/GaN RTD, Resonant Tunneling Diode, Mobility, Transmission coefficient.
PACS: 85.35.Be, 85.30.Mn, 03.65.Xp, 03.75.Lm.

1. Introduction

Recent advances in digital and analog systems demand very high performance electronic circuits such as Resonant tunneling diodes (RTDs). III-nitride have gained interest for RTDs due to wide band gap [1], high carrier mobility and thermal stability that promise high power high frequency room temperature (RT) operation [2]. High aluminum content ($x \geq 0.70$) leads barrier designs leading to large lattice mismatch at the hetero-interface resulting degraded NDR behavior [3-6]. In order to improve material quality and to get reliable and reproducible NDR low aluminum content ($x=0.20$) in $Al_xGa_{1-x}N$ barrier transmission coefficient is observed for varying doping concentration in GaN emitter layer and temperature in presence and absence of applied field. Dislocations occur in GaN emitter layer of AlGaN/GaN RTDs grown on silicon substrate due to large lattice mismatch and different thermal expansion coefficient. This paper consists the variation of transmission coefficient in terms of mobility of carrier in GaN layer which is strongly affected by dislocation density.

---

*) For correspondence, E-mail: subhrachowdhury1987@gmail.com

2. Theory

Time-independent Hamiltonian eigen equation is given by [7]

$$-\frac{\hbar^2}{2m}\frac{d^2\psi(z)}{d\,z^2}+V(z)\psi(z)=E\psi(z) \tag{1}$$

To describe the transfer matrix method the simple scenario in Fig. 1 will be considered first. In region 1 the wave function is termed Ψ_1 and the potential is zero, in region 2 the wave function is termed Ψ_2 and the potential is V_0 and in region 3 the wave function is termed Ψ_3 and the potential is again zero. The solution to the Hamiltonian eigen value equation (1) in these three regions are

$$\psi_1 = \mathrm{A}e^{ik_1z}+\mathrm{B}e^{-ik_1z} \tag{2}$$

$$\psi_2 = Ce^{ik_2z}+De^{-ik_2z} \tag{3}$$

$$\psi_3 = F\,e^{ik_3z}+Ge^{-ik_3z} \tag{4}$$

The wave function (2) and its derivative is required to be continuous at the discontinuity between adjacent regions, i.e. z=0 and z=a. Using the continuity conditions between region 1 and region 2 yields the two equations

$$\psi_1(0)=\psi_2(0) \tag{5}$$

and

$$\frac{d\psi_1}{dz}\Big|_{z=0}=\frac{d\psi_2}{dz}\Big|_{z=0} \tag{6}$$

which gives the following restrictions on the coefficients

$$A+B=C+D \tag{7}$$

$$ik_1A-ik_1B=ik_2C-ik_2D \tag{8}$$

These conditions can be written in matrix form

$$\begin{pmatrix}1 & 1\\ ik_1 & -ik_1\end{pmatrix}\cdot\begin{pmatrix}A\\ B\end{pmatrix}=\begin{pmatrix}1 & 1\\ ik_2 & -ik_2\end{pmatrix}\cdot\begin{pmatrix}C\\ D\end{pmatrix} \tag{9}$$

(9) can be written as

$$\begin{pmatrix}A\\ B\end{pmatrix}=M_{12}\begin{pmatrix}C\\ D\end{pmatrix} \tag{10}$$

M_{12} is known as discontinuity matrix, it describes the propagation of the wave function across boundary. Using the transfer matrix technique (TMT) the final equation for a double barrier single well RTD can be formulated as

$$\begin{pmatrix} A \\ B \end{pmatrix} = M_{12} M_B M_{23} M_W M_{34} M_B M_{45} \begin{pmatrix} K \\ L \end{pmatrix} \tag{11}$$

or

$$\begin{pmatrix} A \\ B \end{pmatrix} = M_s \begin{pmatrix} K \\ L \end{pmatrix} \tag{12}$$

where, (A,B) and (K,L) are coefficients of matrices for wave function profile of contact layers. Ms is known as system matrix.
(10) can be written as

$$\begin{pmatrix} A \\ B \end{pmatrix} = \begin{pmatrix} M_{11} M_{12} \\ M_{21} M_{22} \end{pmatrix} \begin{pmatrix} K \\ L \end{pmatrix} \tag{13}$$

Transmission coefficient can be formulated as the ratio between the flux incident from left side in the barrier and the transmitted flux in the right side, when no incident wave from the left.

$$\mathrm{T}(\mathrm{E}) = \frac{f_{tran}}{f_{\mathrm{int}}} = \frac{|K^2|}{|A^2|} = \frac{1}{|M_{11}|^2} \tag{14}$$

When electric field is applied Schrödinger’s equation will be modified as

$$-\frac{\hbar^2}{2m}\frac{d^2\psi(z)}{d z^2} + V(z)\psi(z) - q\xi(z) z \psi(z) = E\psi(z) \tag{15}$$

Where ζ(z) is the electric field applied along the direction of confinement. Considering new coefficients (A,B) and (C,D) for contact layers, transmission coefficient can be obtained from the following expression

$$T(E) = \frac{|K'^2|}{|A'^2|} = \frac{1}{|M_{11}'^2|} \tag{16}$$

We are considering T2 as T(E) and T1 is the bare single barrier transmission probability.
In order to get unity effective transmission coefficient of the emitter barrier, T1 can be considered as [8]

$$\mathrm{T}_1 = \mathrm{T}_2 + \frac{2L}{l} \tag{17}$$

where, L is the quantum well length, l is the mean free path which is related to mobility of carrier by the relation given below [9]

$$l = v_{avg}\tau_n = v_{avg}\frac{\mu_n m_n^*}{q} \tag{18}$$

where, v_{avg} is the average velocity, τ_n is the mean free time which is related to electron mobility in GaN layer (μ_n). Doping concentration and temperature dependent mobility of electron in GaN is given by [10]

$$\mu_n(T,N) = \mu_{\min}\left(T/300\right)^{\beta_1} + \frac{(\mu_{\max}-\mu_{\min})\left(T/300\right)^{\beta_2}}{1+\left[\dfrac{N}{N_{ref}\left(T/300\right)^{\beta_3}}\right]^{\alpha(T/300)^{\beta_4}}} \tag{19}$$

where, μ_{min}, μ_{max}, N_{ref}, β_1, β_2, β_3, β_4 and α are fitting parameters for this mobility model of GaN.

Considering both scattered and incoherent electrons in transmission, the effective transmission coefficient T_{eff} can be written in terms of mobility of electron in GaN layer grown on virtual buffer [8]

$$T_{eff} = \frac{4\left(\dfrac{2L}{l}+\mathrm{T}_2\right)\mathrm{T}_1}{\left(\dfrac{2L}{l}+\mathrm{T}_2+\mathrm{T}_1\right)^2}\frac{1}{1+\left(\dfrac{\mathrm{E}-\mathrm{E}_n}{\Gamma_n/2}\right)^2} \tag{20}$$

where Γ_n is the resonance width of n-th energy level given by [8]

$$\Gamma_n = \frac{1}{\pi n}\left(\frac{2L}{l}+\mathrm{T}_1+\mathrm{T}_2\right)E_n \tag{21}$$

where, E_n is the resonant level energy measured from the bottom of the quantum well. E_n is given by [8]

$$E_n = \frac{\hbar^2 n^2 \pi^2}{2m^* L^2} \tag{22}$$

3. Results and Discussion

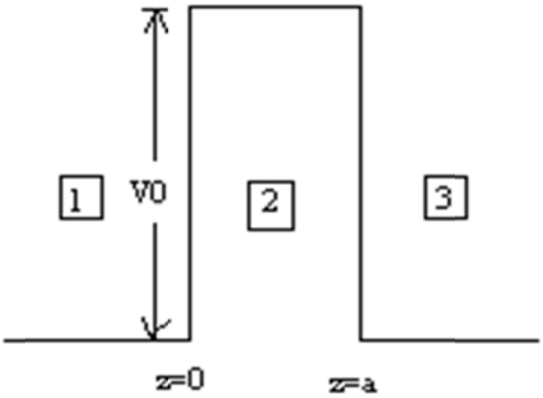

Fig. 1: Tunneling through a single barrier.

Using (1) to (14) and with the help of Fig. 1 transmission coefficient (Tc) of $Al_{0.2}Ga_{0.8}N$/GaN double barrier single well resonant tunneling diode in absence of applied field is calculated. With the help of (1) to (20) Tc is obtained as a function of mobility of carrier in presence and absence of applied field. Barrier width and well width are taken as 2 nm and 1 nm respectively unless otherwise stated. Here the value of V_0 for $Al_{0.2}Ga_{0.8}N$ barrier is considered as 0.42 eV [11] and the value of electron effective mass in hexagonal GaN is taken as 0.222 m_0 [12]. Fermi energy of GaN is considered as located about 0.08 eV above the conduction band minimum (T=300K) [13]. Values of fitting parameters such as μ_{min}, μ_{max}, N_{ref}, β_1, β_2, β_3, β_4 and α for mobility model of GaN in (19) are 295 cm^2/v-s, 1460.7 cm^2/v-s, -1.02, -3.84, 3.02, 0.81 and 0.66 respectively [10].

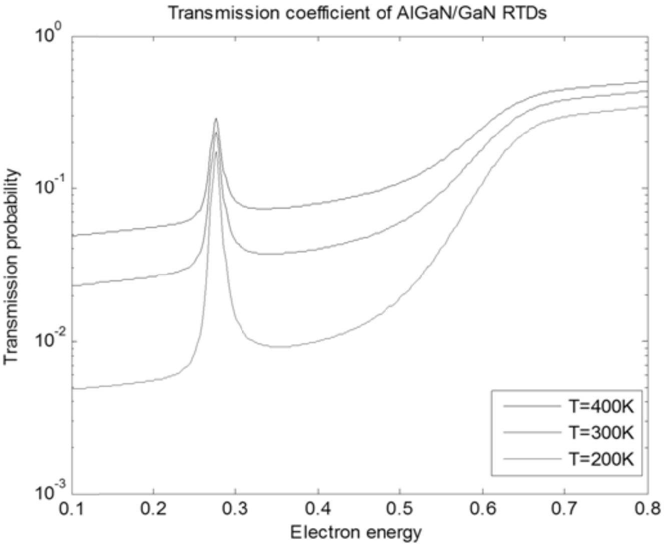

Fig. 2: Variation of Tc with electron energy and temperature in absence of applied field. $N=10^{19}$ cm^2/v-s.

Fig. 2 shows the comparative analysis of transmission coefficient with electron energy and temperature in absence of applied electric field. As the temperature increases Tc increases. A peak is observed at around 0.28 eV and Tc goes to saturation for electron energy above 0.62 eV at all temperatures.

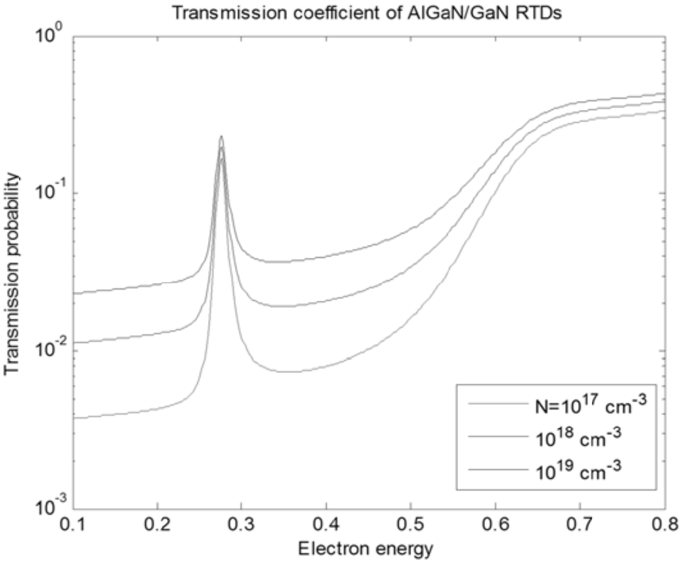

Fig. 3: Effect electron energy and doping concentration of emitter layer on Tc in absence of applied field. T=300K.

Variation of transmission coefficient with electron energy and doping concentration in GaN emitter layer is shown in Fig. 3. With the increase in doping concentration mobility of electron decreases which results in increasing Tc. Here also peak is observed and no interesting details are seen above 0.62 eV where the Tc goes to saturation.

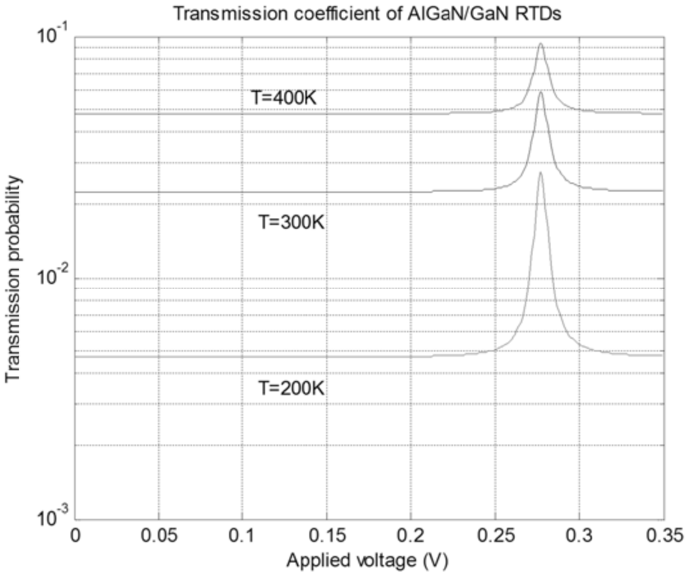

Fig. 4: Comparative analysis of Tc profile for different temperature in presence of applied voltage. N=10^{19} cm^2/v-s.

Fig. 4 and Fig. 5 show the effect of temperature and doping concentration on transmission coefficient in presence of applied voltage respectively. In Fig. 4 Tc is almost constant in the region 0.25 V >applied voltage> 0.31 V at all temperature.

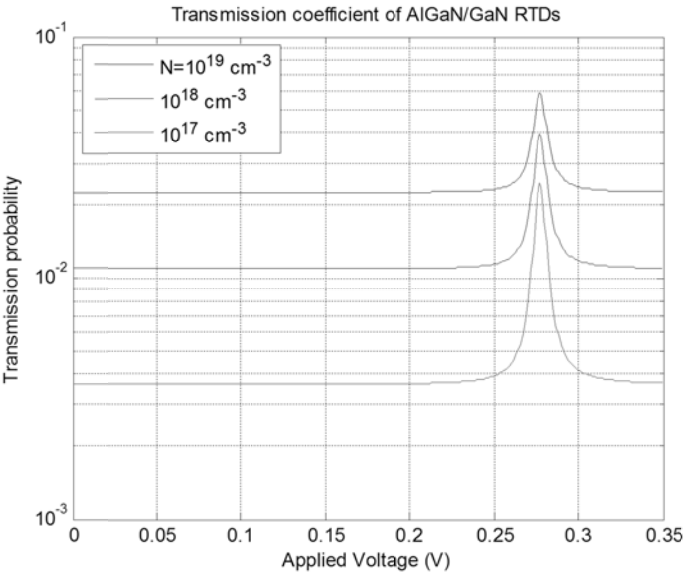

Fig. 5: Variation of transmission coefficient with applied voltage and doping concentration in emitter layer. T=300K.

Fig. 5 shows almost the same result as the previous figure When GaN is grown on silicon substrate due to large lattice mismatch (17 %) and different thermal expansion coefficient dislocation occurs which affects the mobility of carrier in the GaN layer. As the mobility changes transmission coefficient also changes. Due to different growth mechanism of GaN on silicon previous research papers [14-16] show different mobility of electron in GaN layer such as 700 cm^2/v-s, 900 cm^2/v-s, 1350 cm^2/v-s and 1670 cm^2/v-s.

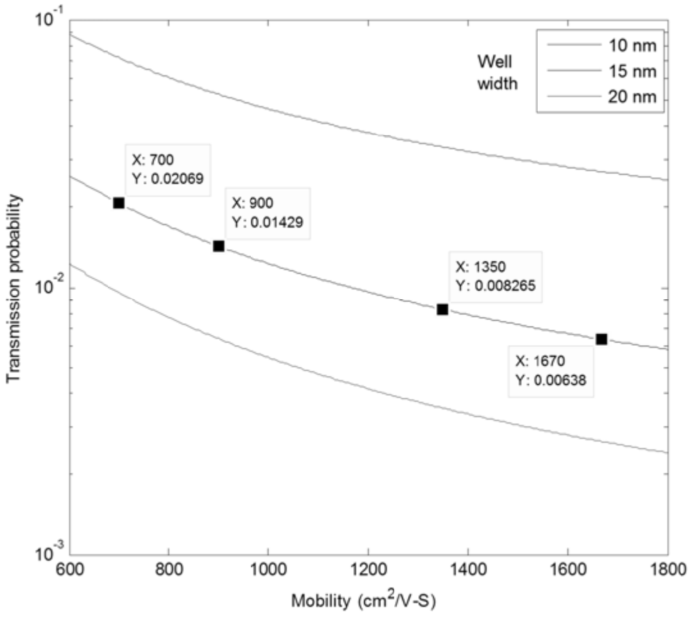

Fig. 6: Mobility of electron in GaN emitter layer versus transmission coefficient for various well width.

Fig. 6 shows the dependence of Tc on mobility and well width. Transmission coefficient decreases almost linearly with increasing mobility of electron for a fixed well width. Tc decreases when well width is higher or equal to 10 nm.

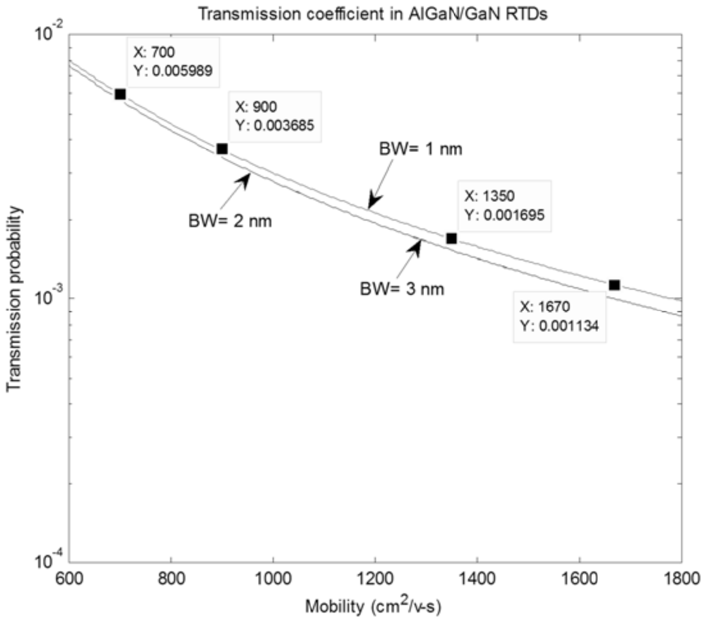

Fig. 7: Variation of transmission coefficient with mobility of carrier in GaN emitter layer for various barrier widths.

In Fig. 7 variation of transmission coefficient with mobility of carrier and barrier width is shown. Tc decreases almost linearly with increasing mobility. As the barrier width increases transmission coefficient decreases. In this figure the graphs of Tc for barrier width 2 nm and 3 nm are so close that they are seen as almost a same line.

4. Conclusion

Results obtained from the analytical modeling of transmission coefficient (Tc) of the proposed $Al_{0.2}Ga_{0.8}N$/GaN RTD structure show that high performance characteristics is possible with the introduction of high temperature and heavily doped GaN emitter layer of this RTD structure. It is concluded that absence of applied voltage is most favorable for AlGaN/GaN RTDs and also thin barrier wide well structure is preferred for maximum transmission coefficient. It is found that Tc does not increase with increasing well width all the time, after a certain well width it decreases.

References

[1] G. Martin, S. Strite, A. Botchkarev, A. Agrwal, A. Rockett, H. Morkoc, W. R. L. Lambrecht, B. Segall, Appl. Phys. Lett., **65** (1994) 610

[2] S. Sakr, E. Warde, M. Tchernycheva, L. Rigutti, N. Isac, and F. H. Julien, Appl. Phys. Lett., **99** (2011) 142103

[3] A. Kikuchi, R. Bannai, K. Kishino, Appl. Phys. Lett., **81** (2002) 1729

[4] M. Hermann, E. Monroy, A. Helman, B. Baur, M. Albrecht, B. Daudin, O. Ambacher, M. Stutzmann, M. Eickhoff, Phys. Status Solidi C, **1** (2004) 2210

[5] S. Golka, C. Pflugl, W. Schrenk, G. Strasser, C. Skierbiszewski, M.Siekacz, I. Grzegory, S. Porowski, Appl. Phys. Lett., **88** (2006) 172106

[6] Z. Vashaei, C. Bayram, M. Razeghi, J. Appl. Phys., **107** (2010) 083505

[7] B. G. Streetman, S. Banerjee, Chapter 2, in Solid State Electronic Devices, 2nd ed. New Delhi, India: Prentice Hall (1986) 40

[8] H. Sheng, J. Sinkkonen, Superlattices and Microstructures, **12** (1992) 453

[9] J. Bernhard, Eur. J. Phys., **30** (2009) 1

[10] M. Farahmand, C. Garetto, E. Bellotti, K. Brennan, M. Goano, E. Ghillino, G. Ghione, J. Albrecht, P. Ruden, IEEE Trans. on Elec. Devices, **48** (2001) 535

[11] C. Bayram, Z. Vashaei, M. Razeghi, Appl. Phys. Lett., **97** (2010) 092104

[12] A. M. Witowski, K. Pakuła, J. M. Baranowski, M. L. Sadowski, P. Wyder, Appl. Phys. Lett., **75** (1999) 4154

[13] P. Perlin, E. Litwin Staszewska, B. Suchanek, W. Knap, J. Camassel, Appl. Phys. Lett., **68** (1996) 1114

[14] P. Javorka, A. Alam, M. Wolter, A. Fox, M. Marso, M. Heuken, H. Lüth, P. Kordos, IEEE Elec. Device. Lett., **23** (2002) 4

[15] K. Cheng, M. Leys, S. Degroote, J. Derluyn, B. Sijmus, P. Favia, O. Richard, H. Bender, M. Germain, G. Borghs, Jpn. J. Appl. Phys., **47** (2008) 1553

[16] E. Chumbes, A. Schremer, J. Smart, Y. Wang, N. MacDonald, D. Hogue, J. Komiak, S. Lichwalla, R. Leoni, J. Shealy, IEEE Elec. Device. Lett., **48** (2001) 420