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Temperature Effect on Potential Barrier of Graphene Nanoribbon Based Schottky Barrier Transistor

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ABSTRACT

Graphene is an interesting material that possesses high electron mobility at room temperature and it is believed to be the potential candidate to replace silicon in current transistor manufacturing. However pure graphene is a gapless material and it is not suitable to be directly used in the fabrication of transistor. In order to solve this problem, graphene nanoribbon is introduced where the graphene is been patterned into few nanometers width nanoribbon. When graphene nanoribbon is patterned as a channel in transistor, schottky barrier is formed at the contact between graphene nanoribbon and the terminal of the transistor. In this paper, the effect of temperature on two schottky barrier properties, depletion region width and potential barrier are studied. As the temperature is increasing, lower value of depletion region width and potential barrier of graphene nanoribbon based schottky barrier are reported. This is due to the temperature effect on the movement of the carriers where the carrier become more energetic as the temperature increases.

1. Introduction

Graphene is a single layer of carbon atoms that arranged in two-dimensional honeycomb lattice, has demonstrated high electron mobility at room temperature (Zhao 2008; Geim 2007; Singh 2011; Wang 2008) which caught many researchers' attention to believe that graphene as a potential candidate to replace the current silicon transistor in the future. However graphene is a gapless two-dimensional material (Choudhury 2008; Zeng 2009; Ahmadi 2010b) which is a major obstacle in electronic application where frequent on/off switching is required. In order to overcome such obstacle, a few nanometers width of graphene called graphene nanoribbon (GNR) is introduced where band-gap is produced by depending on the width and orientation relative to the graphene crystal structure (Han 2007). The smaller the width, the larger the band-gap can produce (Nakada 1996). Another parameter that will affect band-gap in the GNR is the edge effect in the form of edge classification where GNRs can be classified into two categories, which are zigzag GNR (ZGNR) and armchair GNR(AGNR) according to their edge type (Wakabayashi 2009) as shown in Fig. 1. ZGNRs are always metallic, regardless of its width (Zheng 2007), whereas AGNRs exhibit either metallic or semiconducting behaviors, depending on its width. AGNRs will behave like a metallic when the dimer line of GNR satisfies the equation $n=3m+2$ and semiconducting when dimer line satisfies the equation $n=3m$ or $n=3m+1$, where n is the number of dimer lines and m is any integer (Liang 2007).

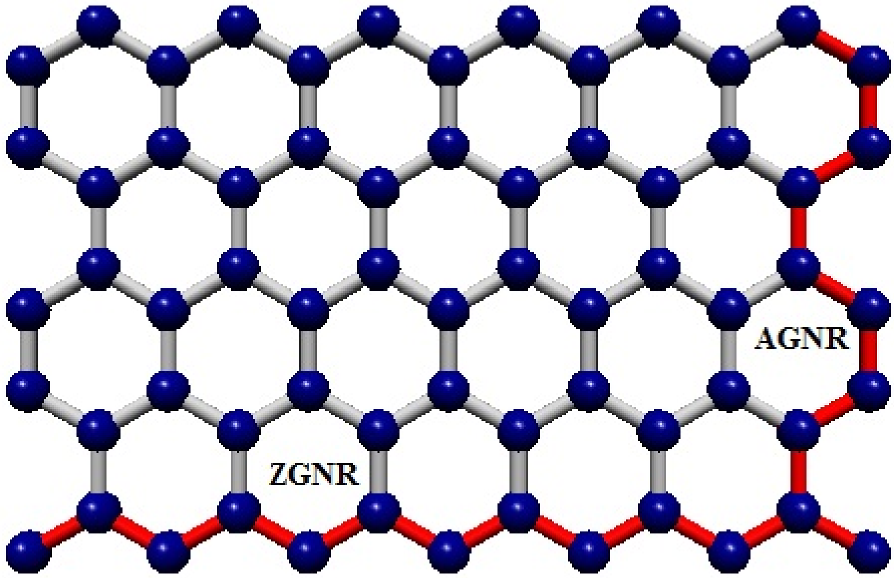

Fig. 1 Zigzag GNR and Armchair GNR

In the proposed GNR based transistor or graphene nanoribbon schottky barrier transistor (GNRSBT), semiconducting AGNR is used as the channel in GNRSBT. The source and drain regions of GNRSBT are usually metals made of palladium (Ouyang 2007). Experimentally, GNRSBTs are constructed by connecting the channel to metals with schottky contacts (Xia 2011). The main focus of this paper is to study the effect of temperature on two schottky barrier properties, which are depletion region width and potential barrier. The model of the depletion region of GNR based schottky barrier is derived based on Poisson equation. The potential barrier is derived by integrating the electric field through space charge region or also know as depletion region(Neamen 1992).

2. Depletion Region Width Model

To obtain the model for depletion region width of one dimensional behavior of GNR, the derivation starts from simple form of Poisson's equation (Neamen 1992):

$$\frac{d\xi}{dL} = \frac{p}{\varepsilon_G} \quad (1)$$

where ξ is junction electric field, L is depletion region width, ε_G is permittivity of GNR and *p* is space charge volume density which is equal to *p* = *nq* where *n* is carrier concentration in GNR, *q* is carrier charge. Band energy of GNR which is a function of E-k dispersion relation have been employed (Ahmadi 2010a). The E-k dispersion relation is expressed as $E = \pm\frac{3ta_{cc}}{2}\sqrt{\beta^2 + k^2}$, which can also be rearrange into $E = \frac{E_g}{2}\sqrt{1 + \frac{k^2}{\beta^2}}$ where $E_g = 3ta_{cc}\beta$. In the parabolic approximation energy relation has been modified as (Ahmadi 2010a):

$$E = \frac{E_g}{2} + \frac{E_g k^2}{4\beta^2} \quad (2)$$

where E is energy, tight bonding energy, *t* =2.3eV, carbon lattice constant, a_{cc} = 0.142nm and *k* is the wave vector. Beta, *β* is defined as $\beta = \frac{2\pi}{\sqrt{3}a_{cc}}\left(\frac{p}{n+1} - \frac{2}{3}\right)$ (Ahmadi 2010b) where *p* is subband index and *n* is the number of dimer. The band energy of GNR in Eq. (2) is used to compute the density of state, DOS of GNR which is defined as $DOS = \frac{\beta}{2\pi\sqrt{E_g}}(E - \frac{E_g}{2})^{-\frac{1}{2}}$ (Redzuan 2011) where E_g is band-gap. It is known that Fermi-Dirac distribution function, *f(E)* is defined as $f(E) = \frac{1}{1+\exp\left(\frac{E-E_f}{k_B T}\right)}$ where E_f is Fermi level, k_B is Boltzmann's Constant and T is the temperature. GNR carrier concentration, *n* is computed from the integration of density of state and Fermi function. Therefore, carrier concentration of GNR can be expressed as:

$$n = \frac{\beta}{2\pi\sqrt{E_g}}\int_{-\infty}^{+\infty}\frac{(E-\frac{E_g}{2})^{-\frac{1}{2}}}{1+\exp\left(\frac{E-E_f}{k_B T}\right)}dE \quad (3)$$

The carrier concentration in Eq. (3) is made with the assumption that the carrier concentration is distributed uniformly throughout the GNR. In other words Poisson's equation can be simplified in the form of:

$$\frac{d\xi}{dL} = N_k\int_{-\infty}^{+\infty}\frac{(E-\frac{E_g}{2})^{-\frac{1}{2}}}{1+\exp\left(\frac{E-E_f}{k_B T}\right)}dE \quad (4)$$

where $N_k = \frac{q\beta}{2\pi\varepsilon_G\sqrt{E_g}}$, which can be integrated as:

$$\frac{\xi}{N_k \int_{-\infty}^{+\infty} \frac{(E-\frac{E_g}{2})^{-\frac{1}{2}}}{1+\exp\left(\frac{E-E_f}{k_B T}\right)} dE} = L + C \qquad (5)$$

where *C* is a constant. It is known that when ξ is zero, *L* is zero also because no electric field exists at the border of the junction therefore the constant, *C* is zero. This means GNR channel depletion width can be modified in the form of:

$$L = \frac{\xi}{N_k \sqrt{k_B T} \int_E^{\infty} \frac{x^{-\frac{1}{2}}}{1+\exp(x-\eta)} dx} \qquad (6)$$

where $x = \frac{E-\frac{E_g}{2}}{k_B T}$, $\eta = \frac{E_F-\frac{E_g}{2}}{k_B T}$. η is normalized Fermi energy which indicates degeneracy limits in the form of its magnitude. Also degeneracy effect on the carrier velocity of GNR based channel will affect carrier movement in the form of Fermi velocity or thermal velocity based on the degeneracy limit. Fermi Dirac integral order negative half $\Im_{-\frac{1}{2}} = \frac{1}{\Gamma(-\frac{1}{2}+1)} \int_0^{\infty} \frac{x^{-\frac{1}{2}}}{\exp(x-\eta)+1} dx$ given by (Ahmadi 2010a) is employed to simplify depletion width on the GNR based schottky barrier.

$$L = \frac{\xi}{N_k \sqrt{\pi k_B T} \Im_{-\frac{1}{2}}} \qquad (7)$$

Based on the presented model of GNR based schottky barrier it is shown that when junction electric field is increased, the depletion region width also increases as shown in Fig. 2. The depletion region width and junction electric field is in linear relationship.

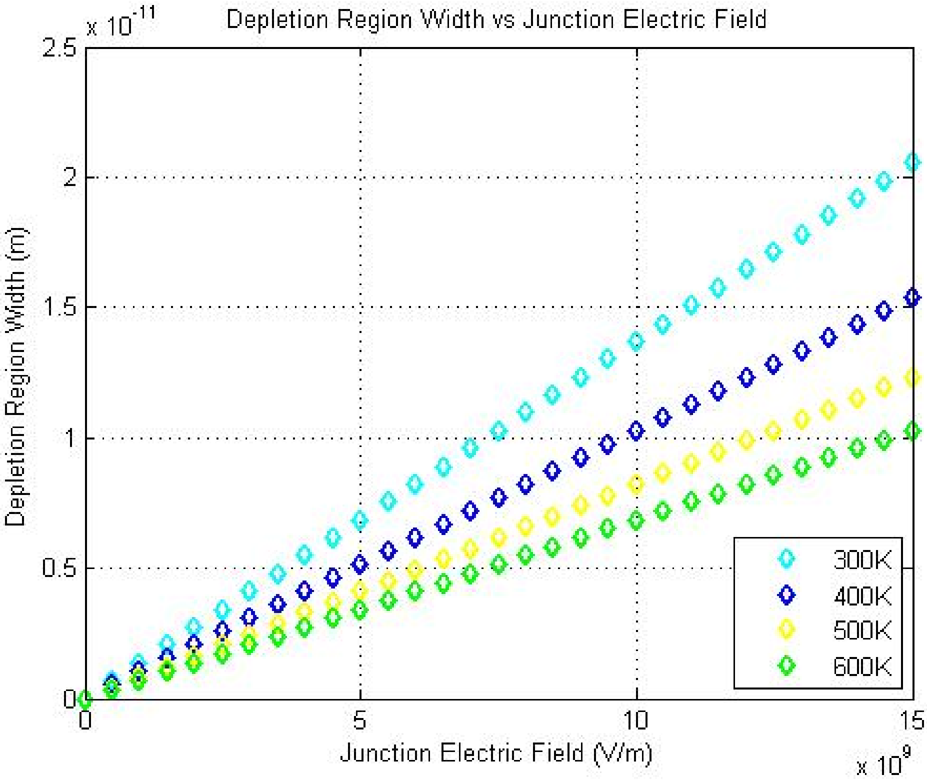

Fig. 2 Graph of Depletion Region Width versus Junction Electric Field with different temperature values

Four different temperature values are used to plot the graph in Fig. 2. In Fig. 2, it is shown that as the temperature increases, the value of the depletion region width is decreasing. At temperature 600K, the depletion region width shows the lowest value compared to the temperature 300K, 400K and 500K. As the temperature increases, the carriers at junction become more energetic and able to travel through the junction. Therefore fewer carriers are accumulated at the junction and it results in lower value of depletion region width.

3. Potential Barrier Model

The model for GNR contact potential barrier, V_{bi} is investigated as:

$$V_{bi} = \int_0^L L N_k \sqrt{\pi k_B T}\, \Im_{-\frac{1}{2}} dL \tag{8}$$

where L is the depletion region width. Integration of the junction electric field through depletion region can obtain the electric potential barrier.

$$V_{bi} = \frac{L^2 N_k \sqrt{\pi k_B T}\,\Im_{-\frac{1}{2}}}{2} \quad (9)$$

Based on the presented model, MATLAB numerical results are plotted to study the relationship between potential barrier versus depletion region width with four different temperature values as shown in Fig. 3.

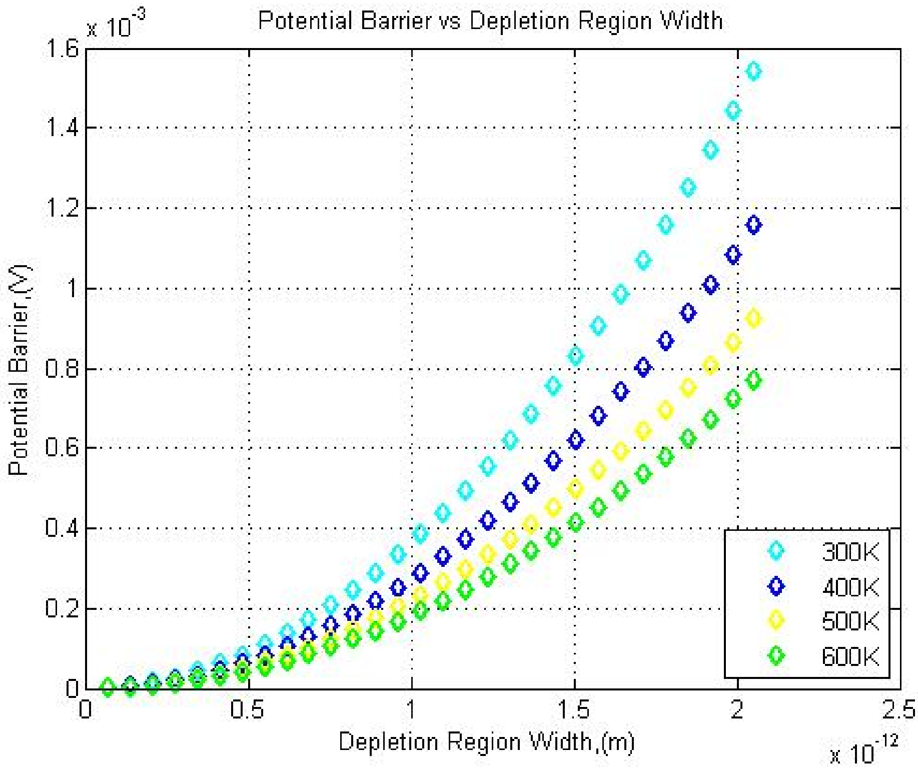

Fig. 3 Graph of Potential Barrier versus Depletion Region Width with different tempareture values

The potential barrier is increased exponentially as the depletion region width is increasing as shown in Fig. 3. As the temperature increases, the value of the potential barrier is decreasing. The potential barrier has the highest value when temperature is at 300K. At temperature 600K, the potential barrier has the lowest value. The temperature affects the kinetic energy of the carriers. As the temperature increases, the carriers obtain more kinetic energy thus have sufficient energy to travel through the junction. Therefore the potential barrier is decreasing because fewer carriers are accumulated at the junction.

4. Conclusion

Graphene holds a great potential in future electronics device due to its high electron mobility. However graphene has one major weakness which is it has zero energy band-gap. This problem is been solved by patterning the graphene into GNR where the width of the ribbon is normally in a few nanometer. The effect of the temperature results in making the carriers more energetic. This cause the depletion region width and potential barrier of GNR based schottky barrier to decrease as the temperature increases.

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References

Ahmadi MT, Ismail R (2010a),"Graphene Nanoribbon Fermi Energy Model in Parabolic Band Structure". In Uksim-Amss First International Conference on Intelligent Systems, Modelling and Simulation. Liverpool, United Kingdom, pp 401-405.

Ahmadi MT, Johari Z, Amin NA, Fallahpour AH, Ismail R (2010b),"Graphene Nanoribbon Conductance Model in Parabolic Band Structure". J Nanomater, Vol **2010**, 1-4.

Choudhury M, Yoon Y, Guo J, Mohanram K (2008),"Technology exploration for graphene nanoribbon FETs". In 2008 45th Acm/Ieee Design Automation Conference, Vols 1 and 2. Design Automation Conference. New York, pp 272-277.

Geim AK, Novoselov KS (2007),"The rise of graphene". Nat Mater, Vol **6** (3), 183-191.

Han MY, Ozyilmaz B, Zhang YB, Kim P (2007),"Energy band-gap engineering of graphene nanoribbons". Phys Rev Lett, Vol **98** (20), 206805.

Liang GC, Neophytou N, Nikonov DE, Lundstrom MS (2007),"Performance projections for ballistic graphene nanoribbon field-effect transistors". Ieee T Electron Dev, Vol **54** (4), 677-682.

Nakada K, Fujita M, Dresselhaus G, Dresselhaus MS (1996),"Edge state in graphene ribbons: Nanometer size effect and edge shape dependence". Phys Rev B, Vol **54** (24), 17954-17961.

Neamen DA (1992),Semiconductor physics and devices: basic principles. Irwin.

Ouyang Y, Yoon Y, Guo J (2007),"Scaling behaviors of graphene nanoribbon FETs: A three-dimensional quantum simulation study". Ieee T Electron Dev, Vol **54** (9), 2223-2231.

Redzuan NB (2011),Modeling the Subband Effects on Graphene Nanoribbon Field Effect Transistor Transport. Universiti Teknologi Malaysia, Degree of Bachelor Thesis

Singh V, Joung D, Zhai L, Das S, Khondaker SI, Seal S (2011),"Graphene based materials: Past, present and future". Prog Mater Sci, Vol **56** (8), 1178-1271.

Wakabayashi K, Takane Y, Yamamoto M, Sigrist M (2009),"Electronic transport properties of graphene nanoribbons". New J Phys, Vol **11** (9), 095016.

Wang X, Ouyang Y, Li X, Wang H, Guo J, Dai H (2008),"Room-Temperature All-Semiconducting Sub-10-nm Graphene Nanoribbon Field-Effect Transistors". Phys Rev Lett, Vol **100** (20), 206803.

Xia F, Perebeinos V, Lin Y-m, Wu Y, Avouris P (2011),"The origins and limits of metal-graphene junction resistance". Nat Nanotechnol, Vol **6** (3), 179-184.

Zeng L, Liu XY, Du G, Kang JF, Han RQ (2009),"Evaluation of Mobility in Graphene Nanoribbons Including Line Edge Roughness Scattering". In 2009 International Conference on Simulation of Semiconductor Processes and Devices. International Conference on Simulation of Semiconductor Processes and Devices. San Diego, CA, pp 222-225.

Zhao P, Choudhury M, Mohanram K, Guo J (2008),"Analytical Theory of Graphene Nanoribbon Transistors". Ieee International Workshop on Design and Test of Nano Devices, Circuits and Systems, Proceedings, Vol, 3-6.

Zheng HX, Wang ZF, Luo T, Shi QW, Chen J (2007),"Analytical study of electronic structure in armchair graphene nanoribbons". Phys Rev B, Vol **75** (16), 165414.