TELKOMNIKA Indonesian Journal of Electrical Engineering
Vol.12, No.4, April 2014, pp. 2530 ~ 2535
DOI: http://dx.doi.org/10.11591/telkomnika.v12i4.4698

Trilayer Graphene Nanoribbon Field Effect Transistor Analytical Model

Meisam Rahmani[1], Razali Ismail[1]*, M. T. Ahmadi[1,2], Komeil Rahmani[3], Ali H. Pourasl[1]
[1]Department of Electronic Engineering, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor Darul Takzim, Malaysia
[2]Electrical Engineering Department, Urmia University, Urmia, Iran
[3]Department of Electrical Engineering, Islamic Azad University Qazvin Branch, Qazvin, Iran
*Corresponding author, email: razali@fke.utm.my

Abstract

The approaching scaling of Field Effect Transistors (FETs) in nanometer scale assures the smaller dimension, low-power consumption, very large computing power, low energy delay product and high density as well as high speed in processor. Trilayer graphene nanoribbon with different stacking arrangements (ABA and ABC) indicates different electrical properties. Based on this theory, ABA-stacked trilayer graphene nanoribbon application as a field effect transistor channel is investigated in this paper. The energy band structure of ABA-stacked trilayer graphene nanoribbon in the presence of a perpendicular electric field using a tight-binding model is presented and the effect of applied voltage on the curvature of the E-K graph is studied. Moreover, an analytical model of carrier statistics for ABA-stacked trilayer graphene nanoribbon in corporation with a numerical solution is presented and current-voltage characteristic of trilayer graphene nanoribbon FET as a one-dimensional device is explored. In fact, the proposed model can be applied as a useful tool to optimize the FET based device performance.

Keywords: *trilayer graphene nanoribbon (TGN), energy band structure, carrier concentration, field effect transistor, current-voltage characteristics*

1. Introduction

Graphene has been discovered as a most promising material with low dimensional physics and possible applications in nano-electronics [1]. It is the flat monolayer of carbon atoms closely arranged in honeycomb lattice. Graphene is also considered to be a hexagonal planar arrangement of carbon atoms, which is the binding structure of the graphitic materials [2-5]. Graphene nanoribbon (GNR) as an advantageous material is among the recently discovered carbon nanostructures with unique characteristics for novel applications. Due to the novel electronic properties such as quantum electronic transport, characteristic charge carriers which behave as massless Dirac fermions, a tunable band gap, long spin-diffusion length thermodynamic stability, extremely high charge-carrier mobility, and excellent mechanical firmness, GNR has attracted worldwide attention for realizing nano-electronic devices in recent years [6-12]. Multi-layers of graphene (MLG) can be piled up independently relying on the horizontal shift between consecutive graphene planes, which results in a variety of electronic properties and band structures [13-14]. The single graphene plane which is two-dimensional (2D) honeycomb lattice is the origin of the stacking order in graphene MLGs with A and B two non-equivalent sub-lattices. Experiments conducted lately about the MLG could be relevant in the creation of new electronic devices [14-15].

Trilayer graphene nanoribbon (TGN) as one of the most common MLGs is shown to have different electronic properties which is strongly reliant on the interlayer stacking sequences [16-17]. There are two known forms of bulk graphite called ABA (AB, hexagonal, or Bernal) and ABC (rhom-bohedral) with different stacking manners as shown in Figure 1 [18]. ABC-stacked TGN and its lattice have three layers as a coupled every coupled has carbon atoms settling on a honeycomb lattice. As shown in Figure 1, A_1, B_1 pairs are located in the top, A_2, B_2 in the heart of layers, and A_3, B_3 in the bottom of layers.

Received August 7, 2013; Revised October 31, 2013; Accepted November 15, 2013

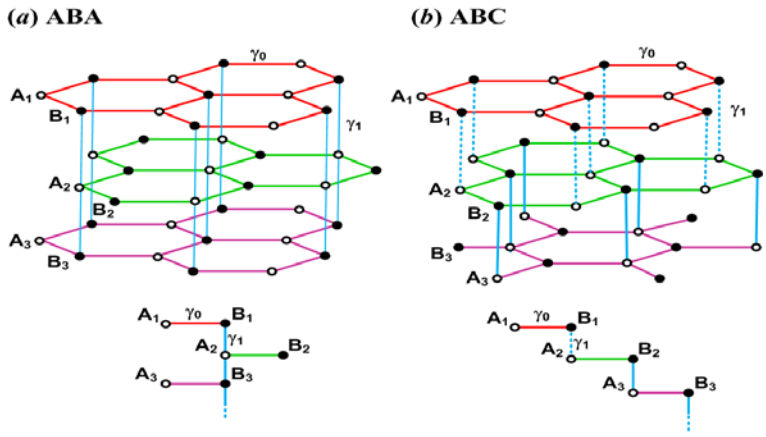

Figure 1. Structures of TGN with (a) ABA and (b) ABC stacking [18]

The stacking order in bulk samples relies on having low energy for that electronic structure [19]. It's notable that the stacking types are highly affecting on the electronic properties of ABA and ABC stacking. Hybrid of low-energy electronic band structure of monolayer and bilayer bands in the presence of interlayer asymmetry is the origin of ABA stacked TGN. Interestingly, ABC stacked TGN and its low energy bands consist of a cubic of monolayer and bilayer together which doesn't look like both simply [18].

TGN based FET can be employed to study the electron transport of graphene, in which a graphene sheet is used as a template on an oxidized silicon substrate and a back gate controlled the current through the graphene. The schematic view of proposed TGN FET is illustrated in Figure 2. TGN with width and thickness less than De-Broglie wave length (10nm) can be assumed as a 1D material. Between two manners of TGN, the semiconducting behavior of ABA stacking structure has turned it into a useful and competent channel material to be used between the source and drain contacts in FET. In fact, the TGN with ABC stacking shows semi-metallic behavior, while the ABA stacked TGN shows a semiconducting property due to its tunable band gap [20].

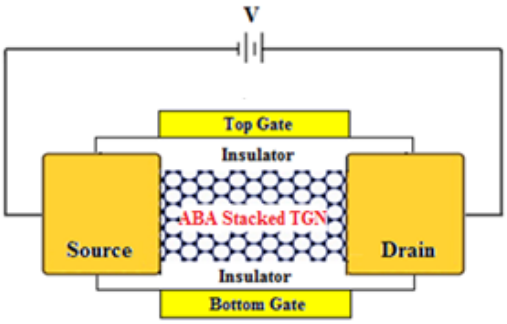

Figure 2. Schematic View of Proposed TGN FET

In next section, the energy band structure of TGN with ABA stacking in the presence of a perpendicular electric field is presented using a tight-binding model. In order to obtain current-voltage characteristic of TGN FET, an analytical model for ABA-stacked TGN carrier statistics is also proposed. The channel current is analytically derived as a function of various physical and electrical parameters. TGN application as a FET channel is investigated in this study and it paves a way for future design of nanosacle FETs.

2. Proposed Model

ABA-stacked TGN energy throughout the entire Brillion zone has been studied by the tight-binding method [21].

$$E_k = \pm(\alpha k - \beta k^3) \quad (1)$$

Where *k* is the wave vector, $\alpha = \frac{v_f \Delta}{t_\perp \sqrt{2}}$, $\beta = \frac{{v_f}^3}{t_\perp \sqrt{2}\Delta}$, which $t_\perp$ is the hopping energy. According to the Equation (1), the band structure of ABA-stacked TGN is plotted in Figure 3. By applying an electric field on ABA-stacked TGN surface, the possibility of opening a gap on band energy emerges, which can be controlled by value of applied voltage. As shown in Figure 3, by increasing the applied voltage, the curvature of the E-K graph increases. It's notable that during this process, not only are the same number of electrons and holes maintained, but also the intrinsic Fermi level will move away from the band gap midpoint

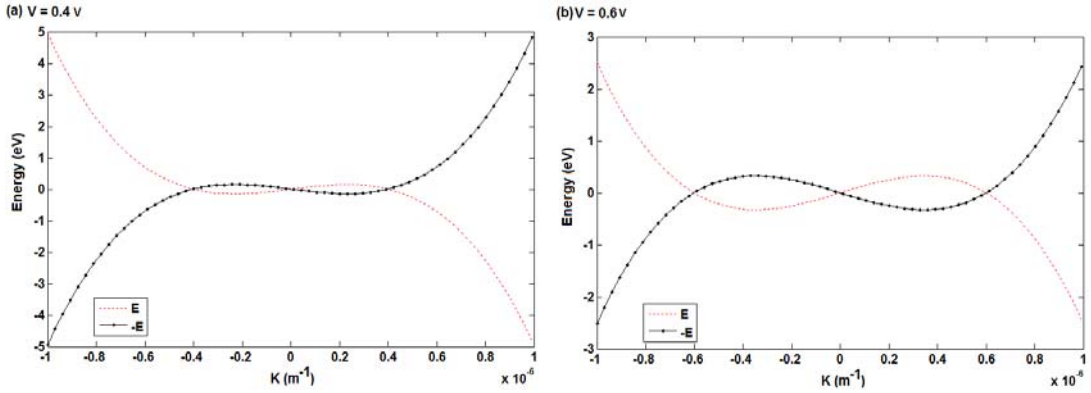

Figure 3. The Effect of Applied Voltage on the Curvature of the E-K Graph in ABA Stacked TGN (a) V=0.4 V (b) V=0.6 V

Carrier concentration as a main parameter is calculated by integrating the Fermi probability distribution function over the energy [22] as:

$$n = \int Dos(E) f(E) dE \quad (2)$$

Where $f(E) = 1/[1 + \exp(E - E_f / k_B T)]$ is the Fermi-Dirac distribution Function. k_B is the Boltzmann constant, E_f is the 1D Fermi energy and T is the temperature. Based on Equation (2), ABA-stacked TGN carrier concentration is modeled as:

$$n = \int_0^{\eta} \frac{(k_B T)dx}{\left\{ A - \frac{B}{(k_B T)^{\frac{2}{3}} \left\{ D(x + E_{CO}) + \sqrt{N + (x + E_{CO})^2} \right\}^{\frac{2}{3}}} - C(k_B T)^{\frac{2}{3}} \left\{ D(x + E_{CO}) + \sqrt{N + (x + E_{CO})^2} \right\}^{\frac{2}{3}} \right\} (1 + \exp(x - \eta))} \quad (3)$$

Where $x = \frac{E - E_c}{k_B T}$, $\eta = \frac{-E_c + E_f}{k_B T}$ or $\eta \approx \frac{V_A - V_T}{k_B T / e}$ (V_A is the applied bias voltage and V_T is the thermal voltage) [23], and *A,B,C,D,F,N,E*$_{co}$ are defined in the Appendix. Based on the proposed analytical model, ABA-stacked TGN carrier concentration is a function of normalized Fermi energy (η) as shown in Figure 4.

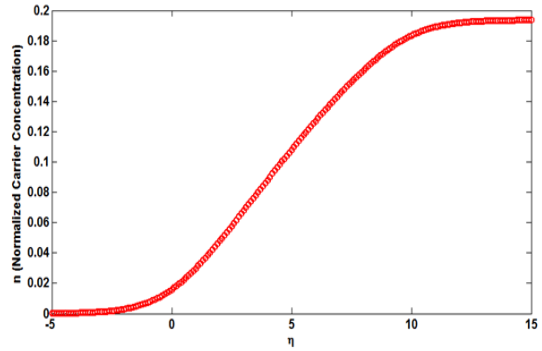

Figure 4. Carrier Concentration of TGN wth ABA Stacking

The current from source to drain is given [24] by:

$$I = n\,q\,.\nu \tag{4}$$

Where n is carrier concentration, q is the electric charge and *v* is the velocity of carries which is defined as:

$$\nu = \frac{\int < \nu > D(E)\, f(E)\, dE}{\int D(E)\, f(E)\, dE} \tag{5}$$

Where D(E) is the density of states and the magnitude of carriers velocity is $< \nu > = \sqrt{\frac{2(E - E_{co})}{m^*}}$. By employing the Equations (3), (4) and (5), current-voltage characteristic of proposed TGN FET is plotted as shown in Figure 5.

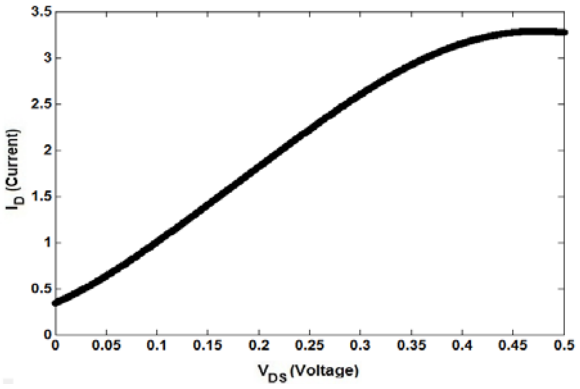

Figure 5. I_D (μA) - V_{DS} (V) Curve of TGN FET

Nano-electronic devices will be scaled down to nanoscale size to meet the Moore's law, and therefore, will operate in the degenerate limit, which makes the degenerate approximation more dominant in the future nanoscale device modeling. It can be concluded that the presented model can be applied as a powerful tool to optimize the FET based device performance.

3. Conclusion

The focus of this paper is to model the TGN based FETs. To address this possibility, the energy band structure of ABA-stacked TGN in the presence of a perpendicular electric field is studied using a tight-binding model. Simulated results indicate that by increasing the applied voltage, the curvature of the E-K graph increases. An analytical model of ABA-stacked TGN carrier statistics is also adopted to derive the current-voltage characteristic of the proposed device. The outcome of this study suggests that TGN FETs have potential to replace conventional silicon FETs in driving the technology forward.

Acknowledgments

Authors would like to acknowledge the financial support from Research University grant of the Ministry of Higher Education (MOHE), Malaysia under Projects Q.J130000.7123.02H24, PY/2012/00168 and Q.J130000.7123.02H04. Also thanks to the Research Management Center (RMC) of University Teknologi Malaysia (UTM) for providing excellent research environment in which to complete this work.

Appendix

$A = -6.2832\ \alpha$, $B = 14.3849\,\alpha^2\beta$, $C = \frac{2.7444}{\beta}$, $D = -9\,\beta^2$, $F = \frac{-0.1690\ \alpha^3}{\beta}$,

$E_{CO} = \frac{E_c}{k_B T}$ and $N = \frac{F}{(k_B T)^2}$

References

[1] GI Zebrev. Graphene nanoelectronics: electrostatics and kinetics. *Micro- and Nanoelectronics*. 2008; 7025; M250-M250.
[2] MT Ahmadi, M Rahmani, MH Ghadiry, Razali Ismail. Monolayer Graphene Nanoribbon Homojunction Characteristics. *Science of Advanced Materials*. 2012; 4; 1-4.
[3] MT Ahmadi, MA Riyadi, I Saad, R Ismail. Numerical Study of Fermi energy For P-Type Silicon Nanowire. *Nanoscience and Nanotechnology*. 2009; 1136: 98-102.
[4] MC Lemme, TJ Echtermeyer, M Baus, H Kurz. A Graphene field-effect devices. *Electron Device Letters*. 2007; 28; 282–284.
[5] MT Ahmadi, LP Michael, R Ismail, Vijay K Arora. The high-field drift velocity in degenerately-doped silicon nanowires. *International Journal of Nanotechnology*. 2009; 6: 601-617.
[6] M Rahmani, MT Ahmadi, R Ismail, MH Ghadiry. Performance of Bilayer Graphene Nanoribbon Schottky Diode in Comparison with Conventional Diodes. *Journal of Computational and Theoretical Nanoscience*. 2013; 10: 1-5.
[7] M Rahmani, MT Ahmadi, H Karimi, MJ Kiani, E Akbari, R Ismail. Analytical Modeling of Monolayer Graphene-based NO2 Sensor. *Sensor Letters*. 2012; 10: 1-6.
[8] M Dragoman, D Dragoman. Graphene-based quantum electronics. *Quantum Electronics*. 2009; 33: 165-214.
[9] SS Shiro Entani, Y Matsumoto, H Naramoto, T Hao, Y Maeda. Interface Properties of Metal/Graphene Heterostructures Studied by Micro-Raman Spectroscopy. *Journal of Physical Chemistry C*. 2010; 114: 20042-20048.
[10] YT Zhang, H Jiang, QF Sun, XC Xie. Spin polarization and giant magnetoresistance effect induced by magnetization in zigzag graphene nanoribbons. *Physical Review*. 2010; 81: 165404.
[11] H Castro Neto, F Guinea, NMR Peres, KS Novoselov, AK Geim. The electronic properties of graphene. *Rev. Mod. Phys*. 2009; 81: 109-162.
[12] MT Ahmadi, Z Johari, NA Aziziah Amin, N Zainal, Razali Ismail. Band energy effect on carrier velocity limit in graphene nanoribbon. *Journal of Experimental Nanoscience*. 2010; 7: 62-73.
[13] A Avetisyan, B Partoens, FM Peeters. Stacking Order dependent Electric Field tuning of the Band Gap in Graphene Multilayers. *Phys. Rev. B*. 2010; 81: 115432.
[14] J Hass, WA de Heer, EH Conrad. The growth and morphology of epitaxial multilayer graphene. *Journal of Physics-Condensed Matter*. 2008; 20.
[15] M Terronesa, A Botello-Méndezb, JC Delgadoc. Graphene and graphite nanoribbons: Morphology, properties, synthesis, defects and applications. *Nano today*. 2010; 5: 351-372.
[16] S Yuan, HD Raedt, MI Katsnelson. Electronic Transport in Disordered Bilayer and Trilayer Graphene. *Phys. Rev. B*. 2009; 82: 235409.

[17] M Aoki, H Amawashi. Dependence of band structures on stacking and field in layered graphene. *Solid State Communications*. 2007; 142: 123-127.
[18] M Koshino. Interlayer screening effect in graphene multilayers with ABA and ABC stacking. *Phys. Rev. B*. 2010; 81: 125304.
[19] F Zhang, B Sahu, H Min, AH MacDonald. Band Structure of ABC-Stacked Graphene Trilayers. *Phys. Rev. B*. 2010; 82: 035409.
[20] H Sadeghi, MT Ahmadi, M Mousavi, R Ismai. Channel Conductance of ABA Stacking Trilayer Graphene Field Effect Transistor. *Modern Physics Letters B*. 2012; 26: 1250047.
[21] F Guinea, AH Castro Neto, NMR Peres. Electronic states and Landau levels in graphene stacks. *Phys. Rev. B*. 2006; 73: 245426.
[22] VK Arora. Failure of Ohm's Law: Its Implications on the Design of Nanoelectronic Devices and Circuits. *IEEE International Conference on Microelectronics*. 2006; 15-22.
[23] S Datta. *Quantum Transport: Atom to Transistor.* New York: Published in the United States of America by Cambridge University Press. 2005; 113-114.
[24] DA Neamen. *Semiconductor Physics and Devices.* Mexico: University of New Mexico. 2003.