Trilayer Graphene Nanoribbon Field Effect Transistor Analytical Model

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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

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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, A₁, B₁ pairs are located in the top, A₂, B₂ in the heart of layers, and A₃, B₃ in the bottom of layers.
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 semimetallic behavior, while the ABA stacked TGN shows a semiconducting property due to its tunable band gap [20].

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 nanoscale FETs.
2. Proposed Model

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

\[ E_k = \pm (\alpha k - \beta k^3) \]  

(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](image)

(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:

\[ n = \int D \omega(E) f(E) dE \]  

(2)

Where \( f(E) = \frac{1}{[1 + \exp(E - E_f / k_B T)]} \) 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:

\[ n = \frac{1}{\left( k_B T \right)^{\frac{3}{2}}} \left[ \frac{B}{(k_B T) \left[ (x + E_{co}) + \sqrt{(x + E_{co})^2 + 4x^2} \right]} - C(k_B T)^{\frac{3}{2}} \left[ (x + E_{co}) + \sqrt{(x + E_{co})^2 + 4x^2} \right] \right] \left[ 1 + \exp(-\eta) \right] \]  

(3)

Where \( x = \frac{E - E_c}{k_B T} \), \( \eta = \frac{-E_c + E_f}{k_B T} \) or \( \eta = \frac{V_A - V_T}{k_B T / e} \) (\( V_A \) 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 (\( \eta \)) as shown in Figure 4.
The current from source to drain is given \[24\] by:

\[ I = n q \nu \]  

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Where \( n \) is carrier concentration, \( q \) is the electric charge and \( \nu \) is the velocity of carries which is defined as:

\[ \nu = \frac{\int <\nu > D(E) f(E) dE}{\int D(E) f(E) dE} \]  

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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.

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.

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Appendix

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

\[ E_{CO} = \frac{E}{k_BT} \quad \text{and} \quad N = \frac{F}{(k_BT)^2} \]

References


