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Modeling of Bilayer Graphene Based Field Effect Transistors for Digital Electronics

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ABSTRACT: Graphene is a wonder material with ultra-fast conductivity due to its zero bandgap structure with outstanding electronic properties. Monolayer graphene based transistors are suitable for analogue electronics as off-state is not required in analogue and radio frequency applications. But to make the bilayer graphene based transistors suitable for digital applications, a bandgap is required for the existence of an off-state. Also, to achieve a higher performance as compared to the rival silicon-CMOS technology, a high I_{ON}/I_{OFF} ratio is required. The latest research on bilayer graphene is still in a theoretical and analytical phase, so we present an analytical modeling of a bilayer graphene based field effect transistor (BLGFET) for digital applications. The proposed BLGFET operates on the principle of a Klein tunneling and Klein paradox. This principle is used to develop a model of BLGFET for digital electronics with an excellent I_{ON}/I_{OFF} ratio (greater than 10^6). Bilayer graphene (BLG) has two types depending on the geometry i.e. AA-stacked and AB-stacked. Both types of BLG undergo Klein tunneling and Klein paradox but at different angles. So the expressions for transmission probabilities and the I_{ON}/I_{OFF} ratios for both types of BLGs are derived and their corresponding results are plotted using MATLAB.

KEYWORDS: Bilayer Graphene Field Effect Transistors, Bandgap, I_{ON}/I_{OFF} ratio, AB-stacked BLG and AA-stacked BLG.

1 INTRODUCTION

In digital electronics, both logic states (on-state and off-state) are necessary for a transistor to be used in logic circuits. But graphene has a zero bandgap, which means it always operates in on-state which corresponds to a very low I_{ON}/I_{OFF} ratio. Monolayer graphene based field effect transistors (MLGGFETs) have the largest I_{ON}/I_{OFF} ratio of 10 [1], which is not enough for digital applications. Several alternate techniques have been proposed based on creation of bandgap such as; by using graphene nanoribbons (GNRs) narrower than 5 nm, which showed the I_{ON}/I_{OFF} ratios up to 10^5 [2]. But the GNRFETs have a very low performance due to the line-edge disorder [3], [4].

Bilayer graphene (BLG) can be used in digital circuits because it has an ability to induce a bandgap necessary of achieving off-state. In BLG, both the layers of graphene are arranged in a way that carbon atoms in top layer exist above the rings of hexagon of bottom layer. In this symmetry, BLG just like single layer graphene (SLG) has a zero bandgap. By applying an electric field on the gate, this symmetry is broken as the atoms of the top layer have the higher potential than the atoms of the bottom layer. This creates a bandgap which is tunable by variation of gate voltage of BLG based GFETs.

In BLG, charge carriers exhibit a tunneling behavior which is also generally known as Klein paradox [5]. According to this behavior specifically for Graphene, the carriers striking the BLG at some angles undergo a total refection and at other angles undergo a total transmission due to tunneling effect. Then the probability of tunneling for charge carriers can be calculated which is subsequently used for finding the I_{ON}/I_{OFF} ratio. This provides a solution for the lack of bandgap in graphene. In [6], a double gated BLG based GFET was used and a bandgap of 250 meV was induced and I_{ON}/I_{OFF} ratio>10^3 was achieved. But a double-gated topology causes a high complexity in circuit modeling and computation of parameters. So we present a single gated bilayer graphene based field effect transistor (BLGFET) for digital applications.

2 Design Structure Of The Proposed BLGFET

The BLGFET model is proposed for digital applications as shown in Fig. 1. BLG undergo a Klein paradox, according to which the carriers striking the BLG at some angles undergo a total refection and at other angles undergo a perfect transmission due to tunneling effect. BLG has two types depending on the geometry: one is the AB-stacked in which both the layers of graphene are arranged in a way that carbon atoms in top layer exist above the rings of hexagon of bottom layer. The other type is AA-stacked in which the top layer is stacked exactly above the bottom layer having the perfect alignment of the carbon atoms and hexagonal rings as shown in Fig. 2 [7], [8]. The carriers striking at normal incidence are perfectly reflected in AB-stacked BLG and are totally transmitted in AA-stacked BLG. This tunneling paradox for carriers in both types of BLGs can be used to develop a BLGFET for digital electronics applications with an excellent I_{ON}/I_{OFF} ratio.

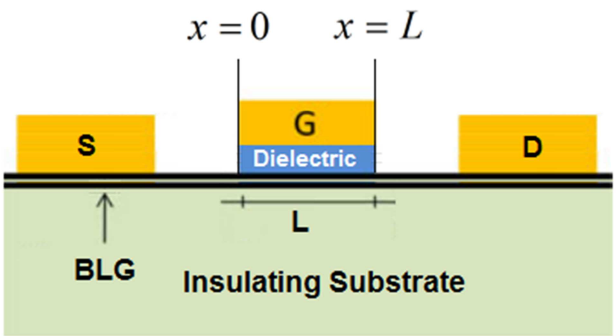

Fig. 1. The proposed BLGFET model for digital electronics applications

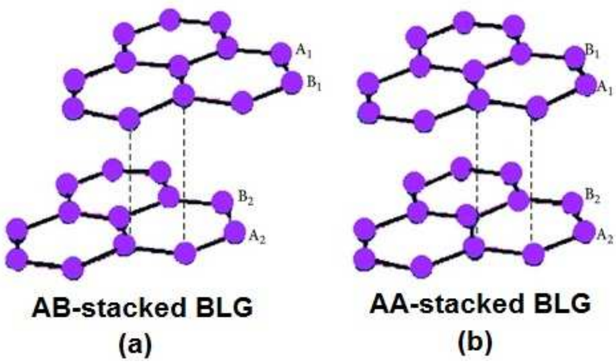

Fig. 2. a) Structure of AB-stacked bilayer graphene, b) Structure of AA-stacked bilayer graphene

3 Modeling Of the proposed GFET For Digital Electronics

3.1 AB-stacked BLG Tunneling through an N-P-N Junction

Using the Klien tunneling concept of AB-stacked BLG in [9], the Hamiltonian of AB-stacked BLG is Dirac-like and is expressed as:

$$H = -\frac{h^2}{2m}\begin{pmatrix} 0 & \left(k_x - ik_y\right)^2 \\ \left(k_x + ik_y\right)^2 & 0 \end{pmatrix} \tag{1}$$

Where 'm' is the effective mass of the charge carriers, 'h' is the planks constant and ($k_x - ik_y$) is the wave vector of BLG. The corresponding eigen-states for this Hamiltonian are formulated as [10]:

$$\psi_A = \left(a_i e^{ik_{ix}x} + b_i e^{-ik_{ix}x} + c_i e^{K_{ix}x} + d_i e^{-K_{ix}x}\right)\cdot e^{ik_{iy}x} \tag{2}$$

$$\psi_B = s_i \begin{pmatrix} a_i e^{ik_{ix}x+2i\phi_i} + b_i e^{-(ik_{ix}x+2i\phi_i)} \\ +c_i h_i e^{k_{ix}x} + \frac{d_i}{h_i} e^{-k_{ix}x} \end{pmatrix}\cdot e^{ik_{iy}y} \tag{3}$$

For each eigenstate, by applying the boundary conditions (at x = 0 and x < L) as shown in Fig. 1, and then taking their derivative gives the following equations:

$$\psi_A^1(x=0) = \psi_A^2(x=0)\ , \qquad \psi_A^2(\mathrm{x=L}) = \psi_A^3(\mathrm{x=L})$$

$$\frac{d}{dx}\psi_A^1(x=0) = \frac{d}{dx}\psi_A^2(x=0)\ , \qquad \frac{d}{dx}\psi_A^2(x=L) = \frac{d}{dx}\psi_A^3(x=L)$$

$$\psi_B^1(x=0) = \psi_B^2(x=0)\ , \qquad \psi_B^2(x=L) = \psi_B^3(x=L)$$

The expression for transmission probability is given as:

$$T(\theta) = |A_3|^2 \tag{4}$$

Where A_3 is the amplitude of the transmitted wave (carrier) between the gate and drain region and θ is the incident angle of carriers. Between on and off states, the current modulation is given by: $1/T(\theta_{\max})$. Subsequently, the I_{ON}/I_{OFF} ratio can be expressed as:

$$\frac{I_{ON}}{I_{OFF}} = \frac{1}{T(\theta_{\max})} \tag{5}$$

Hence, by setting the target I_{ON}/I_{OFF} ratio of 10^6, $\theta_{\max}$ can be calculated as 1.2°. This shows that the GFET is at off-state as long as the carriers strike the n-p-n junction at an angle less than 1.2°.

3.2 AA-STACKED BLG TUNNELING THROUGH AN N-P-N JUNCTION

Using the Klien tunneling concept of AA-stacked BLG from [AA], the Hamiltonian of AA-stacked BLG is expressed as [11]:

$$\hat{H} = \begin{pmatrix} 0 & 0 & \gamma & f(k) \\ 0 & 0 & \overline{f}(k) & \gamma \\ \gamma & f(k) & 0 & 0 \\ \overline{f}(k) & \gamma & 0 & 0 \end{pmatrix} \tag{6}$$

Where, $\gamma \approx$0.2eV which is the interlayer energy and $f(k) = \hbar v_F k e^{-i\theta}$, where θ is the angle of wave vector and $v_F = \sqrt{3}ta/2\hbar \approx 10^6$ m/s is the Fermi velocity. The eigenstates for this Hamiltonian are formulated as:

$$\psi_{\eta_1,\eta_2}(\theta) = e^{ik\cdot r}\begin{pmatrix}\eta_1 e^{-i\theta} \\ \eta_1\eta_2 \\ \eta_2 e^{-i\theta} \\ 1\end{pmatrix} \quad (7)$$

By applying the n-p-n junction based boundary conditions:

$$\psi_i(x=0)+\psi_r(x=0)=\psi_a(x=0)+\psi_b(x=0) \text{ and}$$

$$\psi_a(x=L)+\psi_b(x=L)=\psi_t(x=L)$$

The transmission probability ($T_\mu(\theta)$) is expressed as [11]:

$$T_\mu(\theta)=\frac{\cos^2\phi\cos^2\theta}{\cos^2\phi\cos^2\theta\cos^2(n\pi)+\sin 2(n\pi)[1-\mu\sin\phi\sin\theta]} \quad (8)$$

Where θ is the incident angle of charge carriers, ϕ is the angle of transmitted wave and μ = +1 represents the transmission at a same-chirality and μ = −1 represents the transmission at flipped-chiraliy. Hence, by setting the target I_{ON}/I_{OFF} ratio of 10^6, θ_{min} can be calculated as 69.5°. This shows that the GFET is at off-state as long as the carriers strike the n-p-n junction at an angle greater than 69.5°.

4 MODELING RESULTS

Matlab software was used to implement the equations (4) and (8). In AB-stacked BLG, for an incident angle (θ) = 1.2°, one out of 10^6 carriers undergo transmission by Klein tunneling. So if θ<1.2°, then the AB-stacked BLGFET is at off-state otherwise it is at on-state. So the corresponding Ion/Ioff-ratio of AB-stacked BLBFET is greater than 10^6 as shown in Fig. 3.

Similarly in AA-stacked BLG, for an incident angle (θ) = 69.5°, one out of 10^6 carriers undergo transmission by Klein tunneling. So if θ>69.5°, then the AA-stacked BLGFET is at off-state otherwise it is at on-state. So the corresponding Ion/Ioff-ratio of AA-stacked BLBFET is greater than 10^6 as shown in Fig. 4.

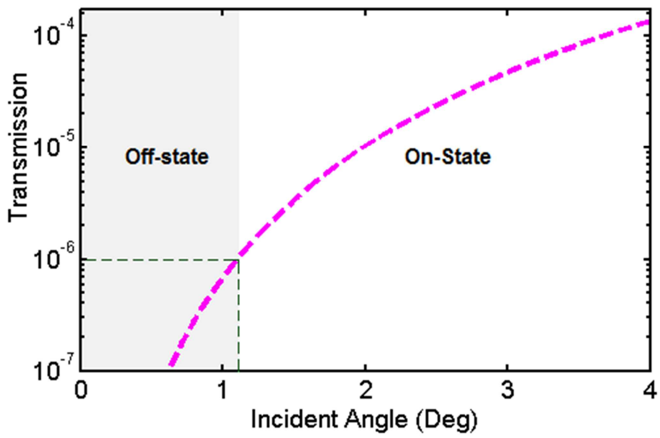

Fig. 3. Transmission probability for an n-p-n junction of AB-stacked BLGFET

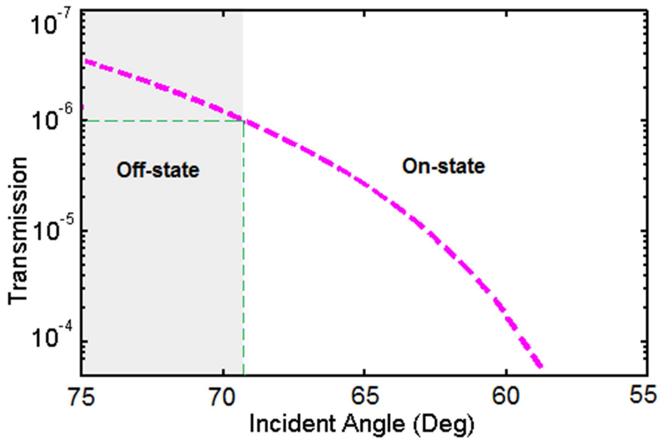

Fig. 4. Transmission probability for an n-p-n junction of AA-stacked BLGFET

5 CONCLUSION

We have presented an analytical model for a top-gated bilayer graphene based field effect transistor. The proposed model is suitable for digital electronics applications as it has a high I_{ON}/I_{OFF} ratio i.e. greater than 10^6. It is shown and verified that both the AA-stacked and AB-stacked BLGFETs undergo Klein tunneling which is dependent on the incident angle of the charge carriers. We have exploited this unique Klein Paradox behavior of BLG to develop the proposed model which can enable the use of GFETs without the requirement of a bandgap. Although bandgap can be created by the process of chemical doping in BLG as shown in [12], but this increases the complexity and manufacturing cost of the BLGFETs.

In our proposed model, the gate of BLGFET is used to control transmission of charge carriers across the p-n junction. This gate-controlled operation is similar to the silicon FETs with a difference that; in BLGFETs, tunneling effect is controlled by the charge carrier's incident angle.

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