Prospect of GNR as Channel Material for Tunnel Field Effect Transistor

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Abstract

The design and simulation of a P-Channel Tunnel Field Effect Transistors (TFETs) with Graphene Nanoribbon (GNR) as channel material is carried out to achieve low sub-threshold swing and high on-off current ratio from the device. A self-consistent iterative method is used to solve one dimensional Poisson equation subject to appropriate boundary conditions and obtain the energy band diagram. The drain current is calculated from the energy dependent tunneling probability and Fermi functions at the source and drain regions. The channel length, ribbon width and gate oxide thickness of the device are appropriately designed to achieve high performance from the device. It is observed that the optimized device provides high ON-OFF current ratio (6.5×10^4) and low sub-threshold swing (8mV/decade), for a channel length of 20 nm and channel width of 4 nm.

Keywords

GNR TFET, Sub-threshold swing, ON/OFF Current ratio

I. INTRODUCTION

Fundamental physical limitation of Silicon MOSFETs in Ultra Large Scale or Giga Scale Integration has led to the proposal of some novel non-classical transistors such as Tunnel Field Effect Transistors (TFETs) as future replacement of Si MOSFETs. In recent years TFETs are attracting the attention of researchers for low-voltage and low power application. The operation of TFETs is primarily dependent on band to band tunnelling (BTBT) of carriers from source and drain to the channel region.

It is reported [1-2] that the magnitude of SS of TFET can be brought down the thermionic limit of 60 mV/decade at room temperature. Tunnel FETs based on lower band gap semiconductor provide higher ON-state current than those based on higher band gap semiconductor. Thus the ON-state current in Ge TFETs is higher than that in Si TFETs. The off-current is however higher in lower band gap such as Ge than in higher band gap, Si. This leads to a degradation of ON-OFF current ratio in Ge TFETs degrading its performance [3].

TFETs with carbon based channel material are reported to excel conventional TFETs as regards subthreshold swing and ON-OFF current ratio. Leem et.al [4] reported that the carbon nanotube heterojunction tunnel field effect transistors (CNT-TFET) provide lower subthreshold swing in the

range of 22- 26mV/decade at a supply voltage 0.2V at channel length 15nm with source drain extension is 10nm and oxide thickness is 1.7nm. TFETs based on Graphene Nanoribbon (GNR) have been proposed in recent years which show excellent performance of these devices as regards lower values of SS and higher ON-OFF current ratio.

Graphene possesses some favourable electronic and physical properties as channel material of TFETs. The electron mobility in Graphene is very high of the order of $10^5 \text{ cm}^2/\text{V-sec}$ [5]. Further the bandgap of GNR can be engineered by varying its ribbon width. It has robust mechanical strength and high thermal conductivity with atomic configuration at the ribbon edge. It exhibits symmetric dispersion relation for both electrons and holes and is less sensitive to doping fluctuation.

Fiori et.al [6] reported that ON-OFF current ratio is more than 10^3 with SS lower than 20mV/decade at a supply voltage 0.1V from a double gate bilayer GNR TFET at channel length 40nm.

The purpose of the present paper is to present a semi-analytical model of a GNR PTFET and analysis of its performance parameters through appropriate design of device structural parameters to realize low value of SS and high value of current ratio at low gate voltage.

II. DEVICE STRUCTURE AND SELF-CONSISTENT MODEL FOR NUMERICAL SIMULATION OF GNR PTFET

The quasi one dimensional geometry of p+ channel GNR TFET device structure is shown in Figure 1. The n+ source, p+channel and p+drain regions are heavily doped with doping concentration by chemical or electrostatic doping process. The doping concentrations of n+ region and p+ regions are taken to be $3.4 \times 10^{20} \text{ cm}^{-3}$ and $1.1 \times 10^{20} \text{ cm}^{-3}$ respectively. A monolayer graphene having thickness (tGNR) of the order of few Angstrom i.e. 3-4Å is deposited over the Si substrate which acts as channel material [7]. A thin layer of high-k dielectric material like Y_2O_3 ($\epsilon_r = 16$) having a thickness (t_{ox}) of 2nm is incorporated in between the gate and GNR.

The channel is assumed to be fully depleted in the OFF state at zero gate voltage. Both the gate and drain are reverse biased with respect to source. The reverse bias gate - source and drain - source voltages are V_{GS} and V_{DS} respectively. The p+ channel is taken in positive x-direction whose length is L_{CH} .

Fig. 1. The structure of a p⁺-channel GNR TFET

The surface potential at any position in the channel region of GNR PTFET can be obtained from numerical solution of one-dimensional Poisson's equation [8] subject to the appropriate boundary conditions.

$$\frac{d^2 \varphi_{\text{surf}}(x)}{dx^2} - \frac{\varphi_{\text{surf}}(x) - V_{GS} - V_{BI}}{\lambda^2} = -\frac{q\rho(x)}{\epsilon_{\text{GNR}}} \quad (1)$$

Where V_{GS} is the gate to source potential, V_{BI} is the built-in potential, $\varphi_{\text{surf}}(x)$ is the surface potential at position x , λ is the screening length for the particular device structure, $\rho(x)$ is the total charge density and ϵ_{GNR} is the permittivity of GNR. The total charge density is approximately equal to the impurity charge density since the source and drain regions are highly doped and channel is assumed to be fully depleted at zero gate bias.

Graphene nanoribbon is obtained by cutting two dimensional graphene sheets in narrow stripes which leads to lateral confinement and induces a bandgap. GNR possesses the unique property of width tunable band gap.

The band gap energy of GNR is related to ribbon width as follows:

$$\xi_G = \xi_C - \xi_V = \xi_{S=+1} - \xi_{S=-1} = \frac{2\pi\hbar v_F}{3w_{\text{GNR}}} \quad (2)$$

Here the width of GNR is much less than its length. Thus the bandgap of GNR depends on the ribbon width w_{GNR} and (v_F) Fermi velocity.

A screening length λ appears in Poisson's given by [9]

$$\lambda = \sqrt{\left(\frac{\epsilon_{\text{GNR}}}{\epsilon_{\text{OX}}}\right) t_{\text{GNR}} t_{\text{ox}}} = \sqrt{t_{\text{GNR}} t_{\text{ox}}} \quad (3)$$

In the above expressions, t_{GNR} and t_{ox} are the thickness of GNR and gate oxide respectively. The permittivities of GNR and gate-oxide are ϵ_{GNR} and ϵ_{OX} respectively. A high-k dielectric material

(Y_2O_3) having a relative permittivity of 16 is used in the analysis. The high-k dielectric material like Y_2O_3 is used to reduce the leakage current from gate to channel. The relative permittivity of GNR is approximated to be same as that of high-k dielectric for simplicity of analysis so that the screening length becomes permittivity independent.

The performance parameters of GNR PTFET are optimized by varying the channel length, ribbon width and gate oxide thickness of the device.

The energy band profile of GNR PTFET is obtained from self-consistent numerical solution of quasi one-dimensional Poisson's equation in source, channel and drain regions subject to the following boundary conditions:

- The electric field falls to zero at the highly doped source and drain ends of the channel.
- Both the electric field and potential are continuous at the source-channel and drain-channel interfaces.
- The separation of Fermi energy level from both the top of the conduction band and the bottom of the valance band are taken to be equal to the thermal energy of the carrier.
- At zero gate bias the valence band in the channel is coincident with the Fermi level at the source end.

The surface potential and barrier height can be extracted from the energy band diagram

At the starting point of iterations, the tunneling injected charges from source to channel (Q_{CS}), drain to channel (Q_{CD}) are taken to be zero. Therefore total channel charge ($Q_C = Q_{CS} + Q_{CD} = 0$) is also zero.

The expression of tunneling probability as a function of energy is given by

$$T_s(\xi) = \exp\left(-2 \int |k_x| dx\right) \quad (4)$$

The expression of the imaginary wave vector is given by

$$k_x = \sqrt{[\xi_C(x) - \xi - \xi_G/2]^2 - (\xi_G/2)^2} \quad (5)$$

The wave vector, k_x is imaginary so that the tunneling probability becomes an exponentially attenuated function and correspondingly the tunneling current wave decays exponentially in the channel. If k_x is real then the tunneling wave will be a propagating one which is not allowed.

Using equation (5), equation (4) can be written as

$$T_s(\xi) = \exp \left(- \frac{2}{\hbar v_F} \int_{x_i}^{x_f} \sqrt{(\xi_G/2)^2 - (\xi_c(x) - (\xi + \xi_G/2)^2)} dx \right) \quad (6)$$

Where x_i and x_f are the initial and final positions of tunneling respectively and $\xi_c(x)$ is the energy at the bottom of conduction band.

The expressions for Q_{CS} and Q_{CD} are given by [10]

$$Q_{CS} = -q \int \rho_{GNR}(\xi) T_s(\xi) d\xi \quad (7)$$

$$Q_{CD} = q \int \rho_{GNR}(\xi) \left[f_D(\xi) \left(\frac{2}{T_s(\xi)} - 1 \right) \right] d\xi \quad (8)$$

In equations (7) and (8), ρ_{GNR} is the density of states function for GNR given by

$$\rho_{GNR} = \frac{1}{\pi \hbar v_F} \frac{\xi}{\sqrt{\xi^2 - (\xi_G/2)^2}} \quad (9)$$

where $\xi > \xi_G/2$ and ξ_G is the band gap of GNR, f_s and f_d denote the Fermi-Dirac distribution functions at the source and the drain respectively, v_F is the Fermi velocity (10^6 m/sec) and $T_s(\xi)$ is the energy dependent tunneling probability.

Substituting the expression of ρ_{GNR} and $T_s(\xi)$ from equations (9) and (6) respectively in equations (7) and (8), numerical integration is carried out to calculate Q_{CS} and Q_{CD} .

The tunneling current from the source to drain is obtained from Landauer formula given below [11].

$$I_D = \frac{q}{\pi \hbar} \int (f_D(\xi) - f_s(\xi)) T_s(\xi) d\xi \quad (10)$$

Numerical integration of the product of tunneling probability, $T_s(\xi)$ and the difference between the Fermi-Dirac distribution functions at the source and drain regions is carried out to obtain the drain current, I_D .

III. SIMULATION RESULTS

The simulated energy band diagrams for the optimized GNR PTFET in the OFF state ($V_{GS} = 0V$) and ON state ($V_{GS} = -0.1V$, $V_{DS} = -0.1V$) are shown in Figs. 2(a) and 2(b) respectively corresponding to the values of w_{GNR} and L_{CH} as 4nm and 20nm respectively. The Fermi energy levels (E_F) in the band diagrams for both the OFF and ON states of the device are also shown. The band-to-band tunneling in TFET depends on the variation of position of the energy band in the channel region with respect to that in the source and drain regions. Fig. 2(b) shows that the applied gate voltage pulls up the energy band

in the channel region in the ON state with respect to that in the OFF state which gives rise to tunneling current.

The OFF current for long channel GNR ($L_{CH} = 20nm$) arises from thermionic emission over the barrier only and direct source to drain tunneling is negligibly small. The OFF current in GNR is calculated from the following equation [12].

$$I_{OFF} = [q^2 V_T / \hbar \pi] \exp(-qV_B / qV_T) \quad (11)$$

re qV_B is the barrier height and qV_T is the thermal energy.

Fig. 2. Energy band diagrams for a GNR PTFET in the (a) OFF-state and (b) ON-state.

The OFF current in GNR PTFET is 0.24pA for a ribbon width of 4nm and channel length 20nm respectively.

Figure 3(a) shows the ON current versus gate to source bias (V_{GS}) for channel length of 20nm and fixed ribbon width of 4nm and oxide thickness of 2nm. The On state current is found 1.58μA. Fig 3(b) shows the ON-OFF current ratio versus gate to source voltage (V_{GS}). The ON-OFF current ratio is found 6.5×10^4 at $V_{GS} = -0.1V$.

Fig. 3. (a) ON current versus V_{GS} of GNR PTFET
(b) ON/OFF current ratio versus V_{GS} of GNR PTFET.

The sub-threshold swing (SS) of a Tunnel Field-Effect transistor is related to the transconductance (g_m) and sub-threshold drain current (I_D) as follows [13]:

$$SS = \ln 10 \left(\frac{g_m}{I_D} \right) \quad (12)$$

The sub-threshold slope (SS) of the optimized GNR PTFET is found to be 8mV/decade at $V_{GS} = -0.1V$. The device shows good switching property due to very low OFF state current and very high value of ON state current. Thus the optimized GNR PTFET will be very much suitable for low power digital application with high ON-OFF current ratio.

IV. CONCLUSION

A p+ channel GNR Tunnel Field Effect Transistor has been designed for optimum performance with respect to higher ON-OFF current ratio and lower subthreshold swing. The values of I_{ON}/I_{OFF} and SS for the optimized device are 6.5×10^4 and 8mV/decade respectively when channel width and length are designed at 4nm and 20nm respectively. The results show that the optimized GNR PTFET will be useful for low power digital application.

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