Analytical Investigation of the Channel Characteristics in Graphene Nano Scroll based Transistors

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Abstract - Silicon-based electronic devices as a three-terminal field-effect transistor is predictably reached to its extreme limitation by getting its channel length below the 10nm regime technology and suffering from numerous scaling drawbacks. As a technology progress, replaced of a new material in transistor channel is considered. Therefore, due to excellent properties, new material as a Nano Scrolls are purposed. These replacements for the traditional silicon-based FET, plays a significant role to increasing the electronic devices speed and performance. However, shrinking of the device dimensions led to challenges such as leakage current, short channel effects, high power consumption, interconnect difficulties and quantum effects, these Nano-device and Nano-structures are the perfect candidate to overcome the scaling problems. In the present paper investigation of the channel scaling and the charge carrier mobility behavior as one of the most remarkable characteristics for modeling of nanoscale Metal Oxide field-effect transistors is considered. This numerical mobility model of charge carrier is modeled analytically for the Graphene Nano scroll Field-Effect Transistor, in which the carrier concentration, channel length and channel's resistance characteristics are highlighted. According to these carrier mobility model of GNS-based FET transistor, the carrier's mobility versus carrier concentration is decreased. Moreover, the channel length increasing caused to growing the channel current. By increasing the channel length, the channel resistance and carrier mobility is ignorable declined. The temperature rising decreases the carrier's mobility and the channel length expanding increases the mobility. Finally, comparison of the model by experimental results, supports the acceptability of model and can maintenance the appropriately of the model outcomes by experimental.

Keywords: Graphene Nano Scroll, Carrier mobility, MOSFET, carrier concentration, channel length, temperature.

1. Introduction

One-atom-thick of carbon atoms by sp^2-hybridized in the honeycomb network with promising electrical, mechanical, and thermal properties, has applications in many scientific fields, such as nan electronics devices. Graphene Nano scrolls (GNSs)and Graphene Nano Ribbons (GNRs), as a new category of quasi-one-dimensional (1D) carbon-based material by their excellent electrical and optical properties, have attracted academics attention in the fields of materials science as shown in Fig.1. There are superior properties such as high optical, electrical and mechanical possessions of GNSs like graphene and Carbon Nano Tube(CNT). The armchair (n, n), zigzag (n,0), and chiral (n, m), as an open multi-walled carbon nanotubes (MWCNTs) are different morphologies of a GNSs with tubular[1] [2, 3]. For example, the structural stability of some of GNS is depended on overlapped surface of rolling. [4-14]. The metallic and semiconductor performance are considered by changing in overlapped surface of rolling in GNS. The edge forms of GNS can be zigzag or armchair types and GNSs are specified by them. The zigzag GNS (ZGNS) possess metallic and semiconductor properties. It is described by (n, 0) chirality number. While (n-1) is multiple of 3 ,ZGNS have metallic properties and in the other value of n , the ZGNS is semiconducting[15].

Short channel effects in the transistor channel of Metal Oxide Semiconductor Field effect transistors as an important challenge in Silicon technology is considered.

Moreover, hot carrier effects and self-heating are main device problems on Silicon based technology. The efforts for replacing the new ways to overcome to this delinquent by candidate material lead to consideration to graphene derivation. The Graphene Nano scroll based transistor channel, due to their uniformity and atomically perfect edge structure, very slim width below 1 nm, and necessary electronic properties is an appropriate assortment to FET. In the present work, it is proposed GNS based as a novel replacement channel structure to overwhelmed the short channel effect problems[16, 17].

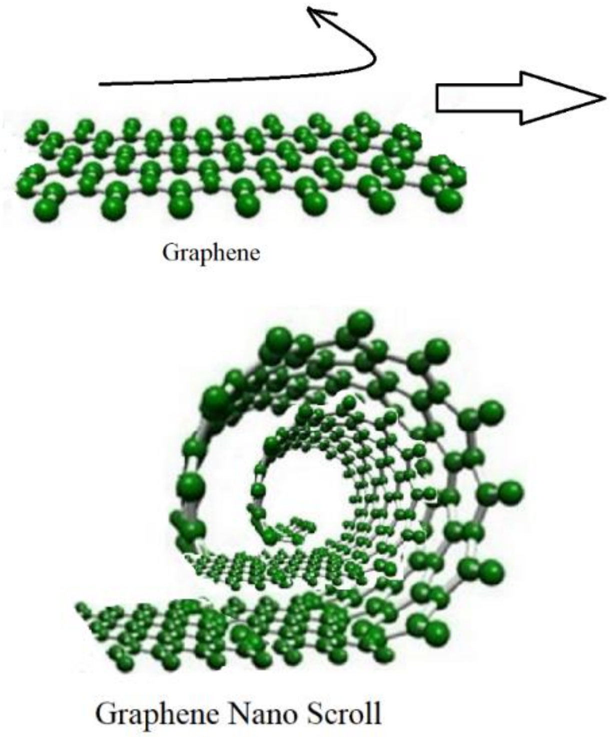


Figure 1: graphene sheet Structure and made of GNS by rolling it into spiral form.

In this case, a better guaranty to performance of Nano scale(FETs) device is determined than the other micro scaling devices. As was mentioned, challenges such as short channel effects due to reduction the device dimensions led to short channel effects, quantum effects, leakage current, high power consumption, interconnect difficulties. Selecting of new materials and device structures to resolve these complications plays a respectable role in achievement of greater productions. As a nomination the GNS structure can satisfy our focus ideas as a channel in Nano scale MOSFETs. As designated, single-gated structure and GNS-based channel MOSFET considered in Figure 2(a, b). The MOSFET based on GNS is assumed and modeled the channel resistance and delay time of carrier in the channel by carrier concentration and mobility. The result is compared by experimental which are in agreement with the recent theoretical predictions [1, 18-20].

2. Model

The carrier's route between crashes will lead to unilateral movement under applied field. Therefore, a drift velocity is produced by them. This drift velocity v_d is in the direction of force qE and so that the transmission carriers will produce current. By average velocity of carrier, v_{av} at any non-zero value of field E, the mean time between interaction or dispersion τ and an effective mobility linking the velocity to E is considered as [21]$v_{av} = \mu E = \frac{q\tau}{m^*} E$, where q is the charge carrier, and m* is effective mass. Furthermore, delay time relation in low-field by μ0 is determined by [21]$\tau = \frac{\mu_0}{q} m^*$,by assumption $\tau = \frac{L_0}{V_T}$,where L0 is the mean free path distance of the carrier (which this amount varies between 0.5 and 5nm [22] amounts) and V_T is the thermal velocity. Moreover ,we calculate the mobility of GNS for small amount of E as;

$\mu_{0GNR} = \frac{q\, L_0}{m^* V_{TH}^2} v_i$ that is linked by the thermal energy ($V_T = \sqrt{\frac{2K_BT}{\pi m^*}}$) [21] ; where v_i represents the intrinsic velocity. In this work for presenting of the mobility in small amount of E, the GNS parabolic band energy model is hired. By considering $v_i = V_T \; \frac{\zeta_0}{\zeta_{\frac{-1}{2}}}$,the delay time and the mobility [21] is obtained as a function of $V_T$as;

$$\mu_{0GNS} = \frac{q}{m^*} \frac{L_0}{\pi V_T} \frac{\zeta_0(\eta)}{\zeta_{\frac{-1}{2}}(\eta)} \qquad (1)$$

$$\tau = \frac{L_0}{\pi V_T} \frac{\zeta_0(\eta)}{\zeta_{\frac{-1}{2}}(\eta)} \qquad (2)$$

where L0 is the mean free path distance of the carrier , the thermal energy(V_T) , ζ is fermi integral order 0 and $\frac{-1}{2}$ and τ is delay time of carrier.

Furthermore, the ion migration flux based on electron drift is given by $J_{sd} = \mu F n_i$;where $F = \frac{\alpha q V}{L}$ is the gradient of the local electrostatic potential and α is fixing factor [23] (-∇Ψ) which is its limit at the top and bottom electrode voltages is between 0V and V_{DS} (source and drain electrode), respectively [24];therefor the drain to source ion flux is achieved by [24];

$$J_{sd} = -\mu \frac{\alpha q}{L_{ch}} \nabla\Psi . n_i = -\mu \frac{\alpha q}{L_{ch}} n_i V_{ds} \qquad (3)$$

where q is the electric charge, $L_{ch} = L$ is the channel length, μ is the mobility of the carriers and n_i is the carrier concentration which is defined as [25];

$$n_i = \frac{2m^*}{3\hbar^2\pi} \sqrt{\frac{k_BT}{t}} \int_0^\infty \frac{(x)^{-1/2}}{1 + \exp\,(x - \eta_f)}\, dx = \left(\sqrt{\frac{2m^* k_B T}{\pi h^2}}\right) \Im_{-\frac{1}{2}}(\eta) \qquad (4)$$

By considering the (3) equation can obtain the resistance of channel as:

$$R = -\frac{W}{L_{ch}} \alpha q n_i \mu = \left(-\frac{W}{L_{ch}} \frac{q^2 \alpha L_0}{\pi V_T} \sqrt{\frac{2k_BT}{m^* \pi h^2}}\right) (\zeta_0(\eta)) \qquad (5)$$

Where w is the channel width. By plotting the resistance of channel and carrier mobility by changing channel length and $L_0 = 3nm$, reducing of the resistance by growing in amount of the carrier mobility is performing. These variation is plotted for channel length between 20 and 100nm in Fig.3.As shown in Fig.3 by increasing the channel length the variation rate is more intense than shorter channels, although these changing are not more noticeable.

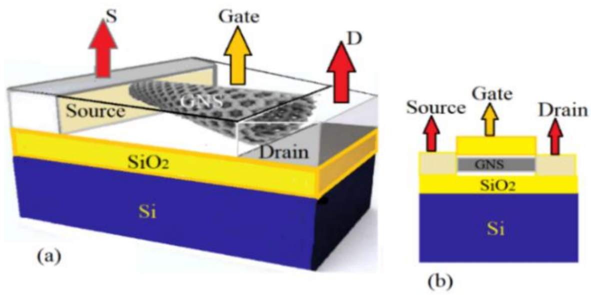


Figure 2 (a, b): Schematic of proposed GNR- based MOSFET. (a)device and (b)the cross section.

As a significant note , the carrier mobility rises with overlap region and remains constant as it reaches GNS Fermi mobility. Therefor signifying ballistic transport near the Fermi point is occurred. According to degenerate and non-degenerate regimes definition, within the band gap, Fermi level with the distance more than 3KBT from either the conduction or valence band edge demonstrates a non-degenerate condition, and within 3KBT of either band edge or lies inside a band is performed the degenerate regime[24]. As shown in the Fig.4(a) the mobility of carrier is reduced by carrier concentration at room temperature and in the shorter channel with less mobility the slop of variation is more tense than longer channel.

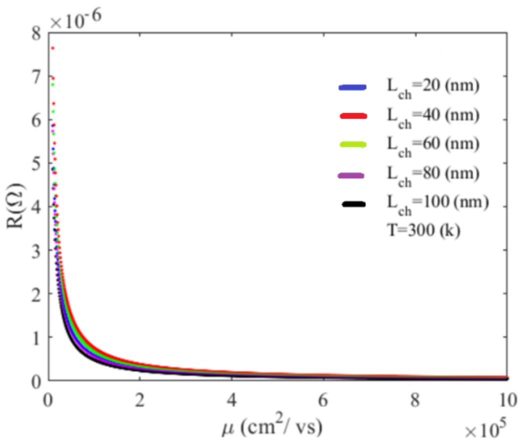
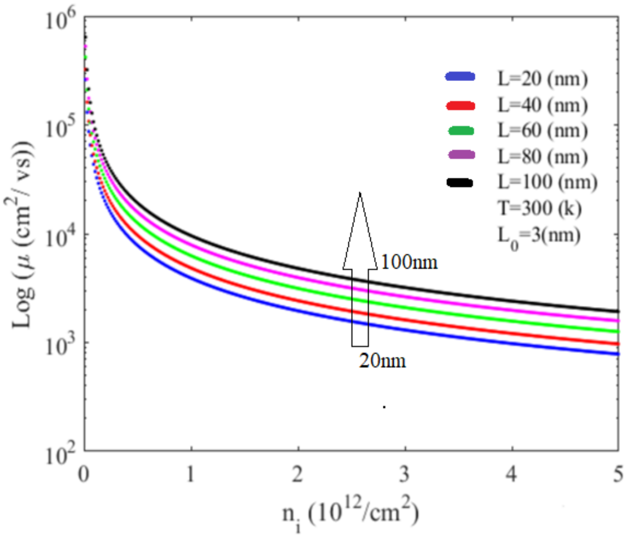


Figure 3. plotting the resistance of channel and carrier mobility by changing channel length.It means that in the transistor by shorter channel current is higher than extended one.

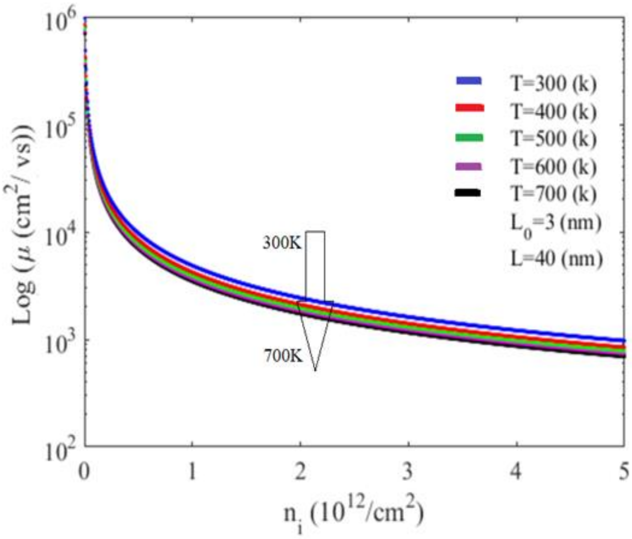
Moreover, the temperature effect on the mobility is shown in the Fig.4(b). The mobilıty variation by carrier concentration by temperature variation between $300°K \leq T \leq 700°K$ is shown in the Fig.4(b). According to model result by growing the temperature mobility is reduced and the amount of decreasing for shorter channel is larger. The (I-V) characteristic of channel plotted in the Fig4. (c). The linear relation between current and voltage is seen in the channel. The shorter channel has higher current.

The light emission controlled, powerfully anisotropic optical absorption, charge-carrier transport limitation and/or ballistic transport, make one-dimensional nanostructures perfect building blocks for applications in electronic, optoelectronic and highly photonic integrated circuits.

(a)



(b)



(c)

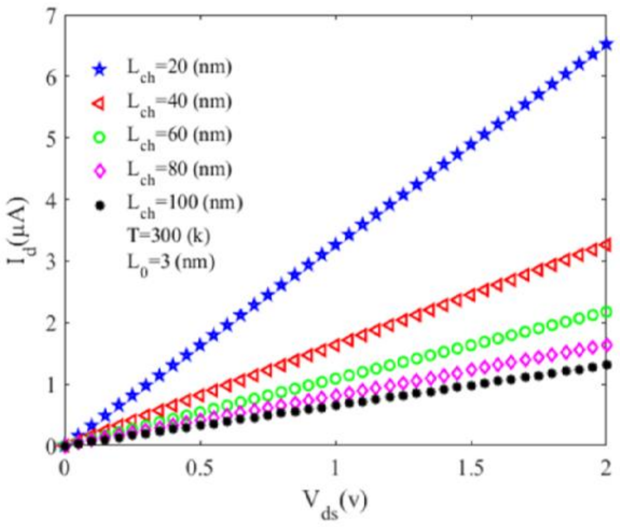


Figure 4. The carrier mobility variation in the channel by carrier concentration. (a) The channel length variation by carrier concentration for different channel length in Nano scale from $(20nm \leq L \leq 100nm)$.(b)the mobility variation by temperature in the 40nm channel length in the room temperature.(c)The Current-voltage characteristics of channel for different channel length$(20nm \leq L \leq 100nm)$.

Recently, is focused on the high (terahertz) frequency devices based on these one-dimensional nanostructures, mainly the semiconductor nanowires and carbon nanotubes [17, 26]. As an alternative, these study results confirmed the significant potential of GNS applications in the silicon-based FETs. It can be concluded that the proposed GNS-based FET would be proper for being employed in different applications of Nano-biotechnology. To support the analytical model results, it is compared by experimental consequences which are shown in the Fig.5. Ballistic transport is defined as freely particle traveling in one direction without more collision by another atom, impurities and defects. It means the mean free path of particles can be reduced and also, it is extended rather to the dimension of particle moving route in the Nano-scale. According to comparison the model supports the experimental grades and the suitable and acceptable outcomes are obtained in the ballistic transports of carriers in the concentration higher than $10^9 cm^{-2}$[27]. The model is following the general model by a good approximately as shown in Fig. (5).

3. Conclusion

The GNS can be an innocent candidate to promising material of the Nano electronic devices in the new subsequent generation. The notable thermal, electrical, mechanical properties such as, high carrier mobility, quantum transport, long spin-diffusion length and thermodynamic stability made great potential applications in Nano electronics. In this research, the charge carrier mobility, delay time and concentration of carrier's charge of graphene Nano scroll-based MOSFET is analytically modeled and the carrier concentration, resistance of the channel dependency on mobility are emphasized. According to analytical results, the charge carrier mobility is improved by channel length and also, channel resistance is decreased by charge carrier mobility. In the other words the shorter channel length by shrinking device dimension and less carrier's mobility and then high channel's resistance is obtained. The carrier mobility is increased due to the current flow and extra carrier creating in the channel length by increasing the applied voltage in the across of the channel. Therefore, in the shorter dimension the applied voltage is smaller and power consumption is less than the others. Furthermore, by increasing the applied voltage across the channel the mobility is increased due to the current flow and extra carrier creating in the channel length. By carrier concentration falling, carrier mobility is amplified in GNS-based FET. As a consequence, the analytical model is appropriate for being employed in different applications of nanotechnology. Consequently, the model is compared by experimental results and shown the acceptable outcomes to support the model.

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