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Carrier velocity effect on carbon nanotube Schottky contact

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One of the most important drawbacks which caused the silicon based technologies to their technical limitations is the instability of their products at nano-level. On the other side, carbon based materials such as carbon nanotube (CNT) as alternative materials have been involved in scientific efforts. Some of the important advantages of CNTs over silicon components are high mechanical strength, high sensing capability and large surface-to-volume ratio. In this article, the model of CNT Schottky transistor current which is under exterior applied voltage is employed. This model shows that its current has a weak dependence on thermal velocity corresponding to the small applied voltage. The conditions are quite different for high bias voltages which are independent of temperature. Our results indicate that the current is increased by Fermi velocity, but the $I-V$ curves will not have considerable changes with the variations in number of carriers. It means that the current doesn't increase sharply by voltage variations over different number of carriers.

1. Introduction

A misunderstanding in the origination of Carbon nanotubes (CNTs) is caused by an editorial written by Marc Monthioux and Vladimir Kuznetsov [1]. But several unrivaled CNT properties have been found and reported from the standpoint of electrical and elastic modulus, respectively. In the near future, they are expected to play a dominant role in the designation of many nano-material based devices [2]. A large percentage of research literature ascribes graphitic carbon as the origin of hollow, nanometer-size tubes [2]. Until 1991, many efforts are done to produce and perceive CNTs under different conditions in order to study their properties. In a research published by Oberlin, Endo, and Koyama in 1976 and by means of a vapor-growth technique, hollow carbon fibers with their nanometer-scale diameters are exhibited vividly [3]. Additionally, a single wall of graphene is demonstrated by the authors in a transmission electro microscopic (TEM) image of a nanotube. Later, this image has been attributed as a single-walled nanotube by Endo [4]. The CNT can be assumed as a single layer graphene rolled up in the cylindrical form as illustrated in Fig. 1.

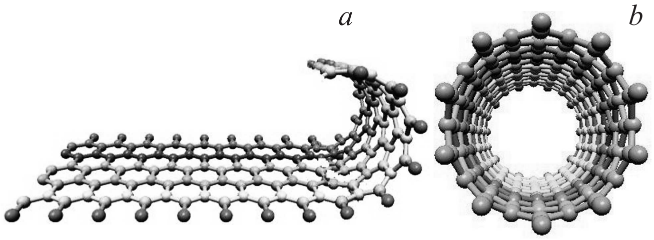

Figure 1. Carbon nanotubes structure as a rolled up graphene.

The strength and flexibility of CNTs are the key factors which make them eligible to control other nanoscale compounds. These factors suggest they will have an important role in nanotechnology engineering. During the recent years, they have drawn the attention of IC designers because of their unique electrical properties [5].

In the criteria of electronic applications, CNTs especially single-walled carbon nanotubes (SWNTs) are supposed as the dominant materials for the next generation of electronic devices [6]. Nowadays, many primary devices are being fabricated using CNTs, including field-effect transistors (FETs), diodes, single electron transistors, nanoelectrodes, and several others [6–8]. Their main advantage was 20−30 times higher ON current in comparison with Si MOSFETs. This was an important advantage in this field as CNT was displayed to potentially perform better than Si [9] and it is because of their higher carrier velocity along with ballistic transport [10,11]. CNT application on schottky transistor provides lower junction voltage in Schottky barrier which means that the ideal diode approximation can be used for it. Also, the schottky transistor can be used with normal diodes and transistors along with the connection of metal or silicide layer to a doped semiconductor layer [12].

Because the metal contacts were one of the important key factors for electronic device performance limitation [13], therefore, Schottky barriers at metal and CNT contacts have been studied extensively [7,14]. However, more understanding and control about the properties of the CNTs are still needed to be done in addition the difficulty of controlling the types, locations, and orientations of SWNTs, a clear realization about the contact between CNTs and macroscopic metal electrodes is need to be explored. In this report the carrier velocity effect on the CNT based schottky contact is explored which indicates that complete saturation does not exist in schottky transistor.

2. CNT based Schottky model

In order to figure out the electrical structure of a CNT, at first its band structure must be obtained. Eq. (1) shows the energy band structure of a CNT [12] which represents a parabolic relationship between E (eV) and the momentum k (nm):

$$E \approx E_{c0} + \frac{h^2 k_x^2}{2m^*}. \tag{1}$$

Where k and m are the wave number and the electron effective mass, respectively. As fundamental parameters, available energy states at a certain energy called Density of state (DOS) has been defined as:

$$DOS = \frac{\Delta n_x}{\Delta E L_x} = \frac{1}{2\pi}\left(E - E_{c0}\right)^{-\frac{1}{2}}\left(\frac{2m^*}{h^2}\right)^{\frac{1}{2}}. \tag{2}$$

The carrier concentration in a band is defined by integrating the distribution function over the energy band by employing Fermi probability function in carrier concentration calculation. Schottky–Mott rule is used to foretell the barrier between a metal and semiconductor which is proportional to the difference of the metal-vacuum work function and the semiconductor-vacuum electron affinity. It must be considered that most of the metal-semiconductor interfaces do not pursue this law to the foretoken degree. Therefore, the effect of Fermi level pinning occurs because the nature of these metal-induced gap states and their occupation by electrons tend to pin the center of the band gap to the Fermi level. The current in metal-semiconductor junction is mostly created by majority carriers, based on thermionic emission theory [15], electrons with energy higher than the height of the barrier will pass the barrier and move towards the barrier. The velocity which is a result of random motion of carriers will affect the current density in the form of:

$$J_s = e \int_1^{N_{\max}} \frac{\int v(E) Dos\, f(E) dE}{\int Dos\, f(E) dE}\, dn. \tag{3}$$

Which leads to the current density as a function of Fermi integrals:

$$J_s = v_{\text{th}} \Im_0(\eta) \ln n. \tag{4}$$

But this random motion does not result to the magnitude of zero for a single vector known as the intrinsic velocity. However, velocity can be discussed in degeneracy limits as shown in Fig. 2, which specifies Fermi integral with Maxwell approximation as an exponential value for Fermi integrals $(F_j(\eta))$ in nondegenerate regime. The average of this intrinsic velocity can be obtained in the form of thermal velocity which indicates temperature dependence motion of carriers as:

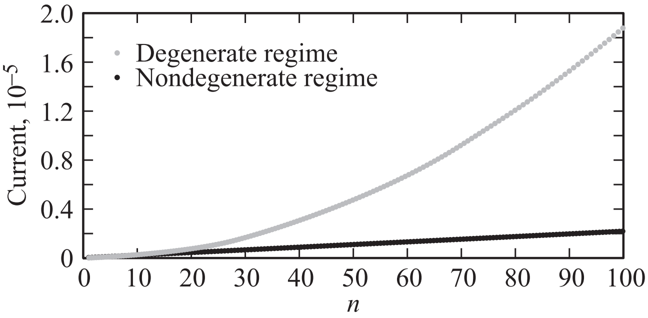

Figure 2. Inherent velocity in degeneracy limit over the carrier concentration.

$$v_{\text{thermal}} = \sqrt{\frac{2k_{\text{B}}T}{\pi m^*}}. \tag{5}$$

Non degenerate limit leads to temperature affected current on schottky contact as shown in Fig. 2.

$$J = en\sqrt{\frac{2k_{\text{B}}T}{\pi m^*}}. \tag{6}$$

On the other hand, in degenerate limit carrier velocity does not illustrate temperature dependent behavior although it shows carrier concentration affected movement of the majority carriers:

$$v_f = \frac{\hbar}{4m^*}(n\pi). \tag{7}$$

Carrier velocity affected by number of carriers known as Fermi velocity (v_f) guides to a parabolic current density relation in degenerate limit as shown in Fig. 2.

$$J = \frac{e\hbar\pi}{8m^*}(n^2). \tag{8}$$

In other words Fig. 2 depict that the intrinsic velocity is a linear function of the carrier concentration in nondegenerate regime (with linear changes) and exponentially in degenerate limit. However, in nondegenerate regime it could be affected by the beginning of a quantum emission [19]. It is required that the velocity is independent of carrier concentration for lower number of carrier as the graph is flat. It seems that most of the previous papers prefer to utilize the thermal velocity for modeling as an independent value of carrier concentration. It is interesting to know that in common the carrier density can be modified in the exponential form as:

$$e^{\frac{J_s}{v_{\text{th}}\Im_0(\eta)}} = n. \tag{9}$$

In terms of our model, the current of CNTs is increased by increasing the temperature in small applied voltage. It is quite different for high bias voltages which are independent of temperature.

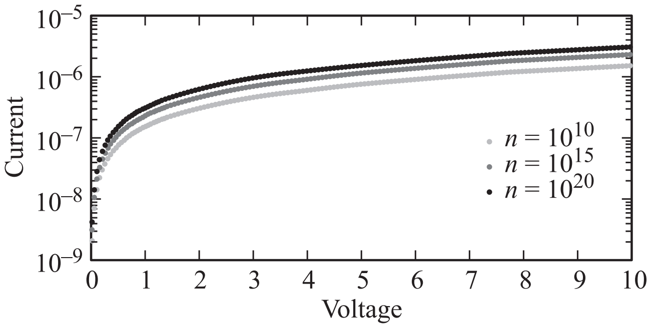

Figure 3. The effect of variations in number of carriers on CNTST $I-V$ characteristic, the yellow curve represents $n = 10 \times 10$, while the green curve is for $n = 10 \times 15$. Finally, $n = 10 \times 20$ is distinguished by blue dots.

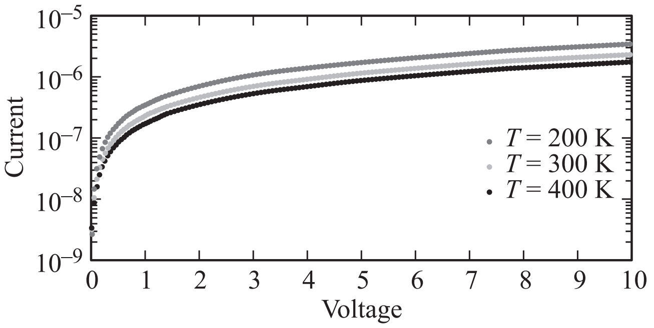

Figure 4. The effect of temperature variations on $I-V$ characteristic.

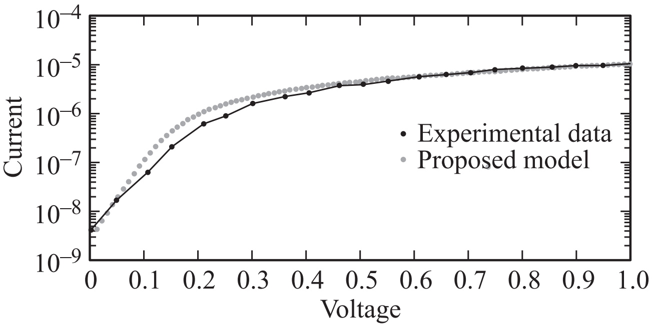

Figure 5. Comparison of proposed model (light dots) with published experimental data (dark line) [20].

According to the simulation results of [20] for effect of the temperature variations on $I-V$ curvature, these variations only take effect on triode region:

$$\frac{dJ_s}{d\eta} = v_{\text{th}} \ln n \int_0^\infty \frac{-e^{-\eta}}{(1+e^{x-\eta})^2}\, dx. \qquad (10)$$

According to the chain rule of differentiation the temperature effect on current-voltage characteristic is explored which indicates that current variation in the saturation region can be clarified by carrier velocity variation. The normalized Fermi energy is expressed by $\eta = (E_F - E_0)/k_{\text{B}}T$ which is a function of temperature that leads to:

$$\frac{dJ_s}{dT} = v_{\text{th}} \ln n \int_0^\infty \frac{\eta e^{-\eta}}{T(1+e^{x-\eta})^2}\, dx. \qquad (11)$$

For better analysis, the effect of temperature variations on $I-V$ Curvature is investigated and current in CNTST as a function of temperature is reported as shown in Fig. 4, in which the green line represents 200 K, the yellow line shows 300 K and the blue line is used for $I-V$ characteristics of the 400 K.

But the simulation results of this work indicate that the temperature variations will affect both of the saturation and triode regions of the transistor. This effect is somehow more sensible in saturation region. Based on the presented model (Eq. 9) it seems that the $I-V$ characteristic cannot be affected sharply by number of carriers as shown in Fig. 3, conversely degenerate limit indicates rapid variation on $I-V$ characteristics. In other words, as illustrated in Fig. 2, the current will be increased dramatically by carrier concentration (n). So, contradicts between the results of Fig. 2 and 5 can be referred as a size effect in the nanoscale devices, also it need to be explored carefully on the basis of nanoscale device saturation and pinch off effects seems to be questionable in nanoscale size as well.

Based on the proposed model for carrier density the numerical result is investigated and $I-V$ characteristics of a CNT — Schottky transistor is simulated as shown in Fig. 3. Since the current doesn't saturate in devices [21], therefore, the saturation velocity and its constitutive quantities need to be discussed more. By focusing on the curvature in Fig. 3, it can be concluded that the presented model for CNT Schottky Contact Current Model indicates the incremental effect of the CNT diameter which can be explained by increasing the current along with the applied voltage. The approach in the analytical models is based on the carrier concentration calculation which most of the time implies the presence of saturation regime in their models. For example, in [15], for Schottky contacts, the transmission through the barrier is particularly considered, in which the gate increases tunneling and serves the thin barrier. For thin gate oxides in contrast with Ohmic contacts, the role of incidental local barriers is supposed to be overlooked.

3. Conclusion

Fabrication of Schottky diode by means of CNT is an open area of research to conquer the limitations of silicon technology. Based on the presented model of CNTST, an increase in the applied voltage will result to an increment in the current which is independent of thermal velocity for the high number of majority carriers. As discussed, the current increases by Fermi velocity in degenerate limit, but the common $I-V$ curve doesn't have considerable changes with the variations in number of carriers and the current doesn't increase sharply by voltage variations over different number of carriers which can be explained in the form of size effect in the nanoscale devices. It is reported that the saturation phenomenon cannot be seen in the nanoscale CNTST comparable to that of conventional FET.

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