Electrical characteristics of a CNTFET and an SB-CNTFET through compact modelling for different chiralities

VIDAL-DE GANTE, Elsa O.†*, HERNÁNDEZ-DE LA LUZ, J. A. David, MOZO-VARGAS, J.J. Martín and LUNA-LÓPEZ, J. Alberto

Posgrado en Dispositivos Semiconductores. Centro de Investigaciones en Dispositivos Semiconductores, ICUAP. Benemérita Universidad Autónoma de Puebla. C.U., Edifs. IC-5and IC-6, Col. San Manuel, C.P. 72570, Puebla, Pue., México.

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Abstract

Objectives, methodology: One of the most important aspects noticed about CNTs is the study of the physics of the one-dimensional (1D) systems in electronics. It is important that the CNFET model, takes into account not only the physic related to this 1D semiconductor device, but also that it allows us to simulate the device behaviour in environments such VHDL or H-SPICE. In this work simulations were made through a generic compact model for two kinds of CNTFETS: a C-CNTFET and an SB-CNTFET. This model includes effects such as the Shottky Barrier created in CNT/metal contacts and the temperature, which may provide I-V characteristic curves more accurate approximating to the real behaviour of a CNFET. Contribution: MOSFET technology made possible an impressive progress in VLSI, given its capability to be scaled and still has also very good performance, however it has been observed that in the nanometric range this kind of devices shows unwanted characteristics, better known as SCEs (short channel effects). One of the most unwanted consequences of these SCEs is that the gate terminal loses some of its control over the transport characteristics. Other ones are the not-controlled quantum mechanical effects, principally tunnelling effects.Some alternatives have emerged to avoid these unwanted effects; one of the most outstanding is that involves carbon nanotubes (CNT). In this work we present the electrical characteristics I-V of a C-CNTFET and an SB-CNTFET, such characteristics were obtained using the compact modelling and considering a SWCNT, with semiconductive behaviour. We use three different chirality indexes (13, 0), (19, 0), (38, 0), which give three different diameters 1.02 nm, 1.48 nm y 3 nm, and energy gaps of 0.8370 eV, 0.5727 eV and 0.2863 eV respectively, such chirality values led to some interesting differences in the I-V response.

CNT, C-CNFET, SB-CNTFET, electrical characteristics, compact modelling

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* Correspondence to Author (email: elsavdg2328@yahoo.com.mx)
† Researcher contributing as first author.

Introduction

This work presents I-V curves of the C-CNTFET and the SB-CNTFET, based on the compact modelling, this model provides a current equation, which is obtained with the assumption that the transport in the CNT is ballistic, in which case is ignored the dispersion effects due to the interaction between electrons and lattice vibrations and defects. This model also includes the height barrier modulation in the source (S) and drain (D) regions, which allows making a comparison between the well-known metal-oxide-semiconductor field effect transistor (MOSFET) and CNTFET, this due to the MOSFET is a device that can modulate the current flow in its channel by modelling the potentials applied on its terminals, gate, source and drain.

While manufacturing a C-CNTFET (Conventional Carbon Nanotube Field Effect Transistor) needs a major technological investment, it is more affordable in these terms to achieve the manufacturing of an SB-CNTFET (Shottky Barrier Carbon Nanotube Field Effect Transistor), so it became important to take into account how including an SB which would change the I-V response.

Normally temperature turns out to be an important factor in semiconductor devices, nevertheless in the case of CNT devices it does not show the same influence, however temperature will always be a factor to take into account in terms of the development of the device.

C-CNTFET

Compact modelling of CNTFET (C-CNTFET) of A. Raychowdhury (Raychowdhury, 2004) it is retaken to investigate the electrical characteristics of a C-CNTFET, this device has an operational mode that resembles to the MOSFET one, in the sense that it is applied the principle of height barrier modulation through the modulation of the potential applied to the gate terminal (V_G).

It is due to its own geometry, that C-CNFET allows this performance, in this geometry the CNT gets wrapped by an oxide of high-κ (dielectric constant), which in a way represents a barrier for tunnelling phenomena, after this material another wrapped corresponding to gate material cover the CNT. Figure 1 shows a squematic arrangement of the CNTFET structure exhibiting the source (S), CNT channel and drain (D), such components are supported by a thin oxide film (SiO_2) followed by a silicon semiconductor substrate type P++.

The portions corresponding to source and drain, are segments of CNT highly doped, both of them will contribute to the flow of current, as it can be seen on current equation below.

Figure 1 C-CNFET arrangement

Current equation

Current equation is derived under the assumption that there is a ballistic transport in the CNT, so in this case is possible to calculate the electrical current which can be derivated from Landauer formula, to stablish that such current is as follows (Raychowdhury, 2004)

$$I_{ds} = \frac{4qk_BT}{h}\sum_{p=1}^{p=n}\left\{\ln\left(1+e^{\xi_S}\right) - \ln\left(1+e^{\xi_D}\right)\right\} \qquad (1)$$

where q is the charge of electron and p indicates the number of sub-bands that contributes to this value of current, besides k_B is the Boltzmann constant, $T(K)$ the absolute temperature and h the Planck constant. The parameters ξ_S and ξ_D are determined as

$$\xi_S = \frac{-\Delta p + q(V_{CNT} - V_S)}{k_BT}, \qquad (2)$$

$$\xi_D = \frac{-\Delta p + q(V_{CNT} - V_D)}{k_BT}. \qquad (3)$$

(2) and (3) are source and drain contributions, and they fill the +k and –k states, which their difference provides the value of V_{DS}, additionally we have that

$$\Delta p = \Delta_1 \frac{6p - 3 - (-1)^p}{4}, \qquad (4)$$

$$\Delta_1 = \frac{0.45}{d} = \frac{E_g}{2}, \qquad (5)$$

where the Δp is the energy of the bottom of the p sub-band and Δ_1 is the bottom of the conduction band, d is the CNT diameter and Eg its energy gap chosen as $0.45eV$ according to this model.

Surface potential

Compact modelling considers the value of the potential in the channel using Poisson equation for getting the next consideration

$$V_{CNT} = V_{GS} \text{ for } V_{GS} < \Delta_1, \qquad (6)$$

$$V_{CNT} = V_{GS} - \alpha(V_{GS} - \Delta_1) \text{ for } V_{GS} \geq \Delta_1.$$

Although it is a valid adjustment one more precise would be given by the next equation (Marki, 2013)

$$V_{CNT} = V_{GS} - 0.5\left\{\alpha(V_{GS} - \Delta_1) + \sqrt{\left(\alpha(V_{GS} - \Delta_1)\right)^2 + 4\varepsilon^2}\right\}. \qquad (7)$$

The modulation of V_{CNT} potential is given by the modulation of V_{GS}, due to the presence of charge in the channel.

SB-CNTFET

For these SB transistors, the SB appears at the interfaces between the semiconducting nanotubes and the metallic leads, i.e. i) the work function of the metal electrodes is higher than that of the nanotubes and/or ii) when the nanotube is supposed to behave as a p-type semiconductor.

As in the C-CNTFET, the principle of functioning of an SB-CNTFET is similar to the MOSFET, this is because gate potential allows decreasing or increasing the height barrier, but one main difference is that the width barrier is modulated by drain bias, the other main difference is the ambipolar I-V response, this is consider by the fact that there is matching contributions of electrons and holes (Marki, 2014).

The approximation in this case came from solving 1-D modified Poisson equation for the channel potential, in order to calculate the effective SB height, which can be expressed as

$$\phi_{SB}{}^{eff} = (\phi_{SB} - V_{CNT})exp(-d_{tunnel}/\lambda) + V_{CNT}. \qquad (8)$$

So the current equation is modified like this

$$I_{DS} = \frac{4qk_BT}{h}\sum_{p=1}^{p=n}\left\{ln\left(1 + exp\frac{qV_S+\phi_{SB}{}^{eff}-sbbd_p}{K_BT}\right) - ln\left(1 + exp\frac{qV_D+\phi_{SB}{}^{eff}-sbbd_p}{K_BT}\right)\right\}. \qquad (9)$$

For a channel length larger than screening length V_D must be consider $-V_D$ (Knoch, 2008).

Temperature effect

In order to include the temperature effect in the current equation it is useful to consider the temperature dependence of the band gap of semiconducting single-wall carbon nanotube, this value is derived from the direct evaluation of electron-phonon coupling within a "frozen-phonon". A useful model relation Eg (T) of semiconducting SWNTs in the temperature range of T<400 K is that as a two phonon Viña model (Capaz, 2005) which gives the following equation:

$$\Delta E_g(T) = \frac{\alpha_1\Theta_1}{e^{\Theta_1/T}-1} + \frac{\alpha_2\Theta_2}{e^{\Theta_2/T}-1}, \text{ (eV)} \qquad (10)$$

$\Theta_1$and Θ_2 are effective temperatures for the two "average phonons", these parameters have a direct relation with the SWNT diameter and chirality:

$$\Theta_1 = \frac{A}{d^2}, \qquad (11)$$

where $d = \sqrt{n^2 + m^2 + nm}$, and

$$\Theta_2 = \Theta_2{}^{\infty} + \frac{f_{\Theta_2}(\xi)}{d}, \qquad (12)$$

$$\alpha_2 = \frac{1}{d}\left(B + \frac{f_{\alpha_2}(\xi)}{d}\right), \qquad (13)$$

$$\alpha_1 = \alpha_1{}^0 + f_{\alpha_1}(\xi)d. \qquad (14)$$

It is possible to introduce this effect in the current equation by modifying (2) and (3) as it follows:

$$\xi_S = \frac{-E_T+q(V_{CNT}-V_S)}{k_BT}, \qquad (15)$$

$$\xi_D = \frac{-E_T+q(V_{CNT}-V_D)}{k_BT}, \qquad (16)$$

where $E_T = E_0 + \Delta E_g(T)$ and $E_0 = \frac{2a_{cc}|t|}{d}$, $a_{cc} = 1.42$Å and $t = -3eV$.

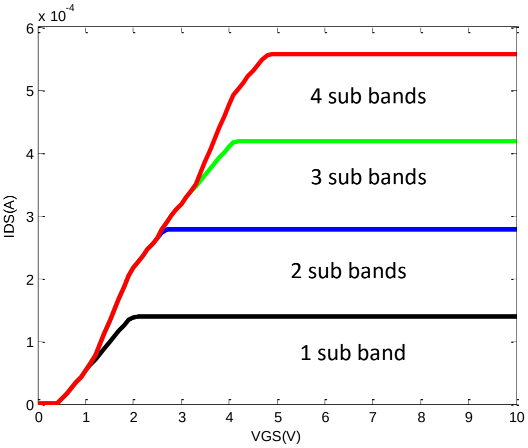
As it was mentioned above the compact modelling allows including many different factors that can modify the electric response in this type of devices, so in this work it is included the temperature effect as well as the SB effect in the current equation as it is introduced in the following equations

$$\xi_S = \frac{-E_T+qV_S+\phi_{SB}{}^{eff}}{k_BT} \quad , \qquad (17)$$

$$\xi_D = \frac{-E_T+qV_D+\phi_{SB}{}^{eff}}{k_BT}. \qquad (18)$$

Results

By virtue of the MOSFET and CNTFET work based on the height barrier modulation which depends on the value of gate potential V_G applied on the CNT, thus the energy level in the source and drain barriers decreases producing a major electron flow through the CNT channel. So the current value will depend on the number of carriers in the different sub-bands. The number of the sub-bands to take into account depends on the applied gate voltage (Raychowdhury, 2004). In graphic 1 it is possible to see how each band contributes to current value, so there is a minimum value of current curve just with 1 sub-band and the biggest value is obtained with the contribution of 4 sub-bands, however it is also possible to see how chirality affects the I-V response, and the one which exhibits better response corresponds to (38, 0) chirality.



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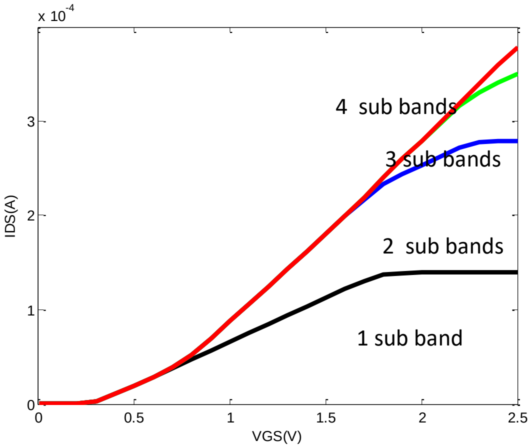

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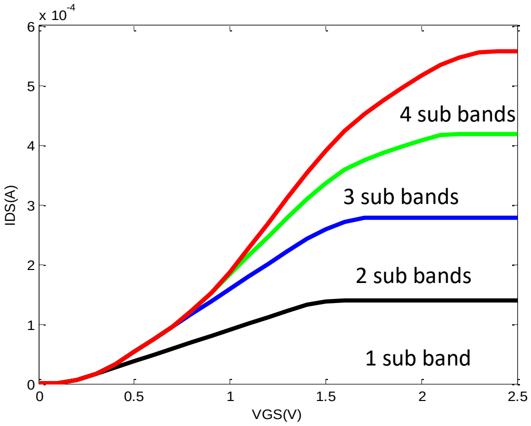
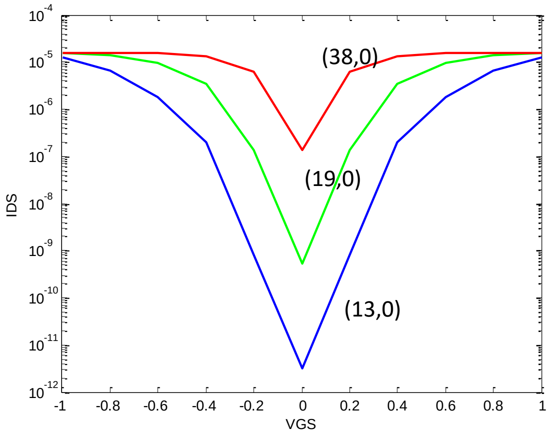


c)

Graphic 1 I_{DS} vs V_{GS} V_{DS}= 0.9 V for a) (13, 0), b) (19, 0), c) (38, 0) chirality and the contribution of 4 sub-bands.

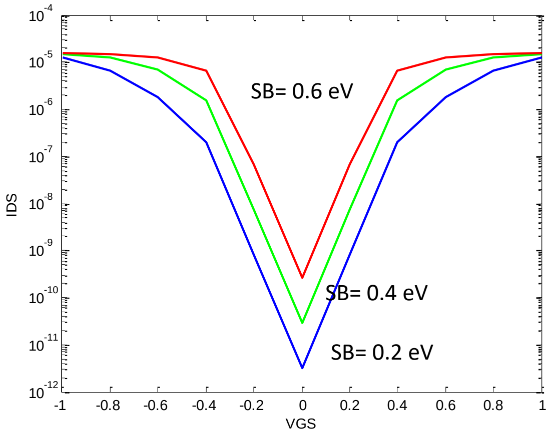
In the case of graphic 2 it is possible to see how the I-V response changes when, instead of ohmic contacts there is an SB contact formed in the interface CNT/metallic gate, in this case appears the ambipolar characteristic given for electrons and holes contribution. As it happens in C-CNTFET response, SB-CNTFET response is also very sensitive to changes in the chirality index, so in the case where the chirality index is the smallest one (13, 0), and the band gap has the value of 0.8370eV, the current value will be the biggest one, and it happens the opposite when the chirality index is the biggest one, (38, 0) and the band gap has the value of 0.2863 eV.



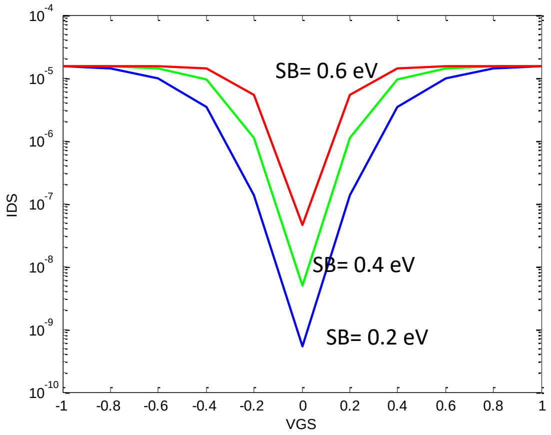
Graphic 2 I_{DS} vs V_{GS} for three different chiralities indexes (13, 0), (19, 0), (38, 0),V_{DS}=0.1V, SB=0.2 eV, d_{tunnel}= 4.125 nm, λ_S=3.29nm

It is predictable that by introducing different materials in contacts there SBs would have different values, so electrical response will also be different, and as it has seen before chirality index will also modified speed of response and current value. In graphic 3 it is possible to see two different aspects in each graphic, the first aspect is that when there are smaller SBs there will be a smaller current value, which is almost predictable because is only carriers with energies bigger than SB which would reach the channel (Marki, 2014).

On the other hand, the current would also be decreased when chirality index has a bigger value.



a)



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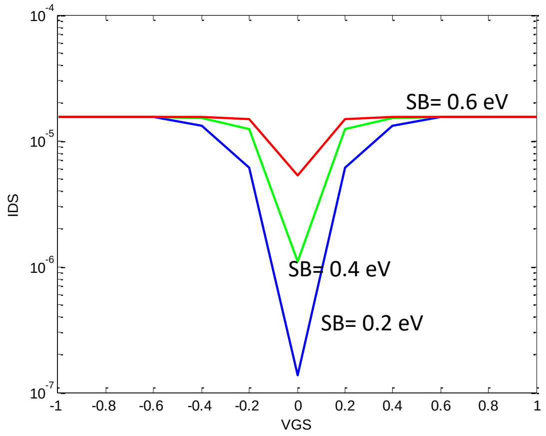
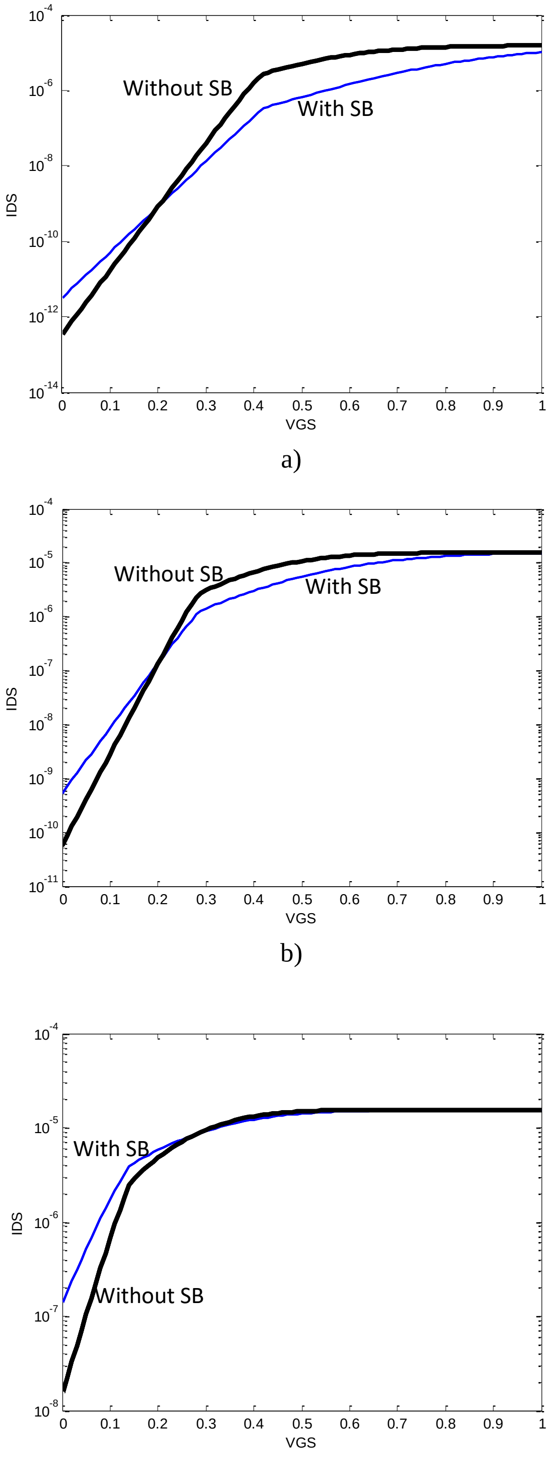


c)

Graphic 3 I_{DS} vs V_{GS}, V_{DS}=0.6V, for a) (13, 0), b) (19,0), c) (38,0) and three different SBs=0.2eV, 0.4 eV, 0.6eV, d_{tunnel}=4.125nm, λ_S=3.29 nm

The next graphics, 4 and 5 allows comparing clearly how much the current value changes in both devices, with and without the SB effect, in all cases it is remarkable that the current diminishes with the presence of the SB effect as consequence of the obstruction of the flow carriers due to the barrier formed in the interface of the contact CNT/metal. It is more visible the differences in the case of I_{DS} as a function of V_{DS}. In both graphics, 4 and 5, there were used the following chiralities, a) (13, 0), b) (19, 0) and c) (38, 0).

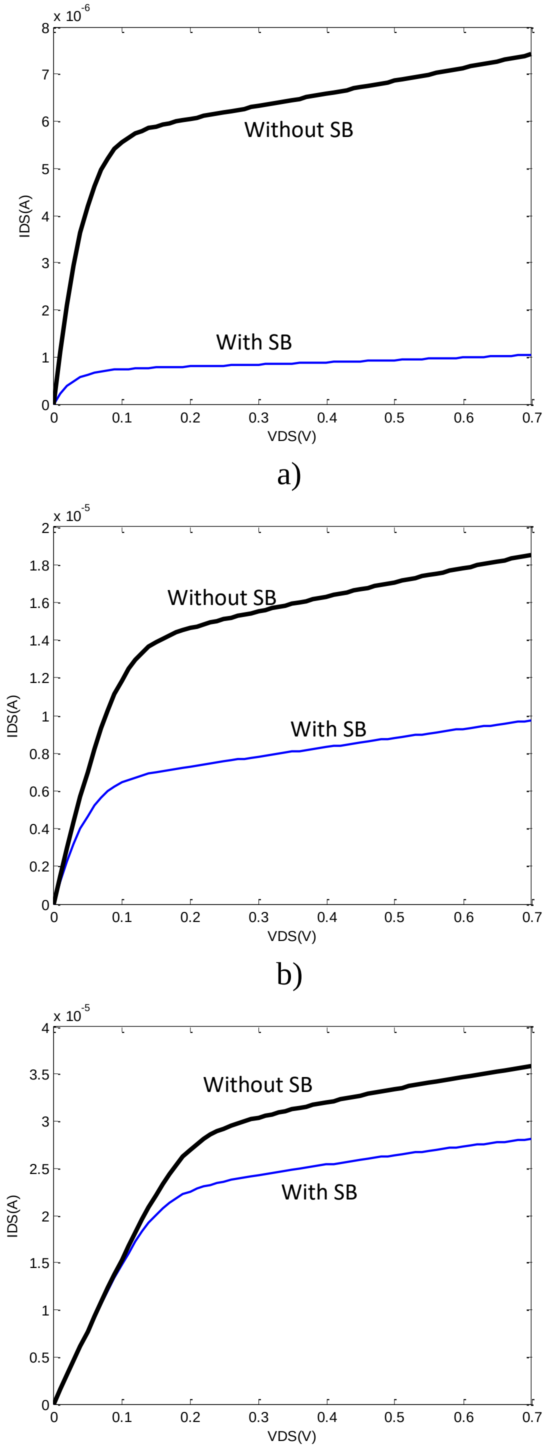


a)

b)

c)

Graphic 4 I_{DS} vs V_{GS} with SB=0.2 eV and without SB, V_{DS}=0.1 V



a)

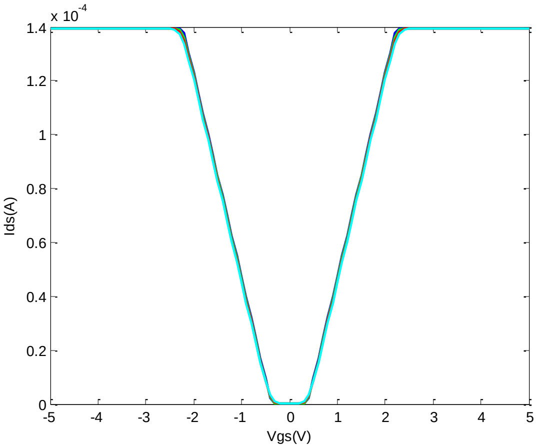
b)

c)

Graphic 5 I_{DS} vs V_{DS} with SB=0.2 eV and without SB, V_{DS}=0.1 V

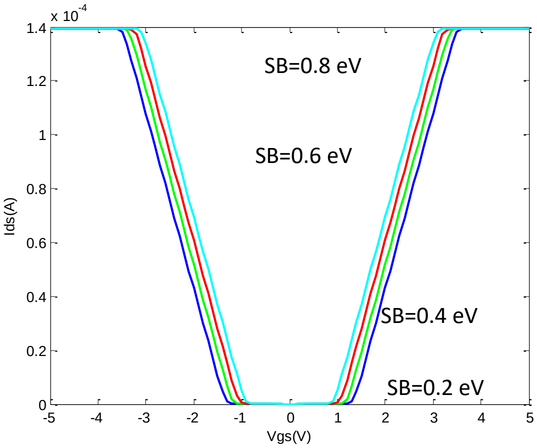
In graphics 6 and 7, temperature effect was introduced, as well as some variations for SBs values and the three different chiralities considered for previous simulations.

It is observable in graphic 6 that variations of temperature from 100 K- 400 K do not introduce significant changes in the I-V response, where we are also taking into account CNT/metal contact.



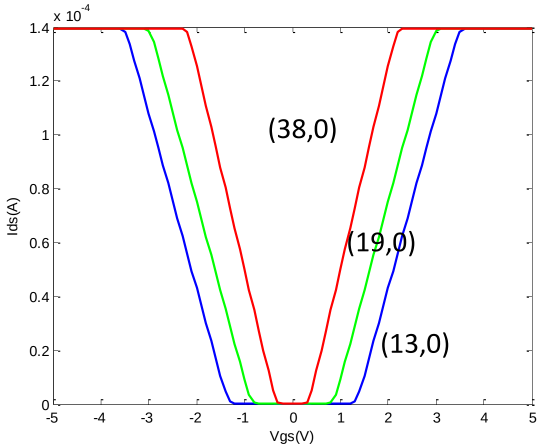
Graphic 6 I_{DS} vs V_{GS}, effect of temperature for T ranging from 100 K- 400 K, SB= 0.2eV, V_{DS}= 0.9 V, d_{tunnel}= 4.125nm, λ_S=3.29nm.

For graphic 7 variations in SBs values effectively show changes in current response, making it slower, in this simulation temperature was established in a value of 200 K.



Graphic 7 I_{DS} vs V_{GS}, V_{DS}=0.9V, SB=0.2 eV, 0.4eV, 0.6 eV, 0.8 eV, chirality index (38, 0), dt_{unnel}=4.125nm, λ_S=3.29nm, for 200 K

Finally, for graphic 8, temperature was settled in a value of 200 K, the SB has a value of 0.2 eV, in this case there was a variation in the value of chirality index, and it certainly modifies the response, for the biggest chirality index response turns out to be faster than for the smaller values.



Graphic 8 I_{DS} vs V_{GS}, V_{DS} = 0.9 V, three different chirality indexes (13, 0), (19, 0), (38, 0), SB = 0.2 eV, d_{tunnel} = 4.125nm λ_S=3.29nm.

Conclusions

It is outstanding how the geometrical characteristics have such a big influence on the electrical behaviour. In first place it is remarkable how diameter, which is directly related to chirality index, determines how fast it can be the I-V response, and also that finding the right diameter would provide a cleaner response.
Another important factor that makes the I-V response more sensitive it is taking into account the Shottky Barrier formed in CNT/metal contacts, the materials used in these contacts would determine the SB value, however the value of SB clearly diminishes the current value, this diminution is also determined by the value of the chirality index, which in appearance as big it is the diminution in current is lesser.

In the range of the temperature established for this work it is hard to notice a strong influence over current values, although it is possible to see again how an SB and chirality index give the bigger changes in value and fastness in current curves.

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