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Electrical characteristics of a Carbon Nanotube Field- Effect Transistor (CNTFET)

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Abstract

In 1965 Gordon Moore predicted that it would have been possible to duplicate the number of transistors in a chip per year. Since then, the number of transistor has increased 3200 times. However it has been predicted that CMOS technology, which is the base of IC's in these days, will reach some important limitations, specially for re-scaling devices into nanoscale regime. In this matter, one of the most interesting options to improve or replace this technology is the use of carbon nanotubes (CNTs) devices, due to their unique electrical and structural properties. In this work we present the electrical characteristics of a CNFET by the I-V behavior, where we have considered a basic geometry, after CNT junction, in order to describe the CNTFET electrical performance. This I-V characteristics were obtained using a compact modelling, and considering a single wall CNT (SWCNT), with semiconductive behavior, in the case, its chirality index is (38,0), and a 3nm diameter, which provides a energy gap Eg of 0.3 eV. In our model we take the approach that the electrical transport in a SWCNT obeys ballistic transport it is posible to get a drain current equation based on Landauer formalism, which takes into a ccount the ideal ohmic contacts approximation, also it allows observing the contribution to the I-V value of the electronic charge present in the CNT sub-bands, in that case, it was interesting to observe that the bigger contribution to the I-V was made by the two first sub-bands.

1D system, CNT, C-CNFET, electrical characteristics

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

In this work is necessary the management of the 1D physical aspects, which is the case of the CNTFET, this is due to there is a need to reduce the scale of the devices. One of the areas of electronic technology which requires this procedure is the integration in large scale, so it is necessary to introduce in an small area a huge number of these devices, and they operate as the MOSFET devices do.On the other hand, one of the advantage that is present in the CNTs devices is that the great and unique properties, such as electrical, mechanical, thermical, are intrisec of these CNTs, which is already found in nanometer scale, this situation does not happen in the case of a semiconductor crystal, which necessarily most be designed with the purpose of achieve certain features specially for the design of nanodevices.

C-CNTFET

Compact modelling of CNTFET (C-CNTFET) of A. Raychowdhury [2] it is retaken to investigate the electrical caracteristics of a C-CNTFET, this device has an operational mode that resembles to the MOSFET, in the sense that it is applied the principle of height barrier modulation through the modulation of the potencial applied to gate terminal (VG).

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 (SiO2) 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.

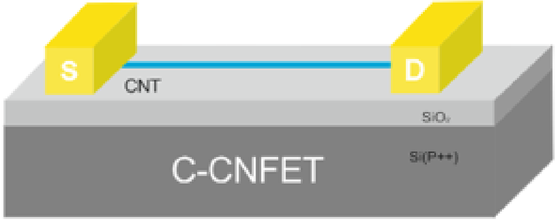


Figure 1 C-CNFET arrangement

Current equation

As it was mentioned before the current equation in the CNTFET is derived under the assumption that there is a ballistic transport in the CNT, so in this case is possible to calculate current can be derivated from Landauer formula, to stablish that such current is as follows [1]

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

Where q, is the charge of electron and p indicates the number of sub-bands that contributes to this value of current, besides is the Boltzmann constant, the absolute temperature and the Planck constant. The parameters ξ_S and ξ_D are determined as

ξ_S=(-Δp+q(V_CNT-V_S))/(k_B T) (2)

ξ_D=(-Δp+q(V_CNT-V_D))/(k_B T) (3)

(2) y (3) are source and drain contributions, and they fill the +k and –k states, which their diference provides the value of VDS, additionally we have that

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

$$\Delta_1 = \frac{0.45}{d} = \frac{E_g}{2} \tag{5}$$

Where the Δp is the energy of the bottom of p sub-band and Δ1 is the bottom of the conduction band, is the CNT diameter and Eg its energy gap chosen as 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

$$V_{CNT} = V_{GS} \text{ for } V_{GS} < \Delta_1 \tag{6}$$

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

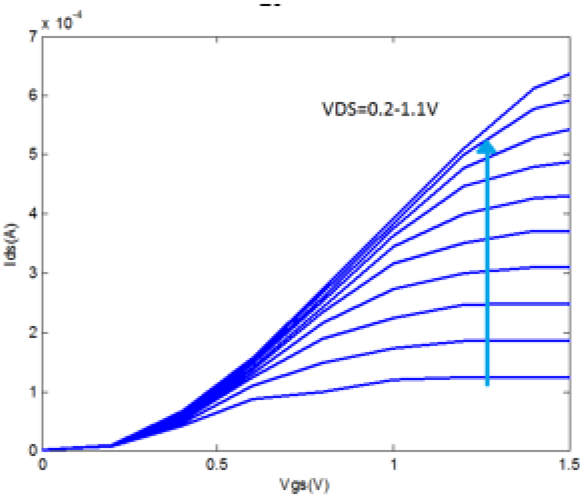
Althought it is a valid adjusment one more precise would be given by the next equation.

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

The modulation of VCNT potential is given by the modulation of VGS, due the presence of charge in the channel.

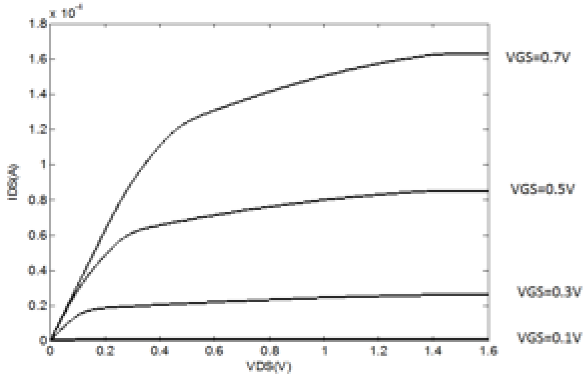
Results

When the gate potential VG applied on the CNT increases the energy level in the source and drain barriers decreases producing a major electron flow through the CNT channel. That is the main reason that makes the carrier population increases in each sub-band in the CNT, so there is a need to take into account the contribution of more sub-bands of energy. This fact generates an increment in the channel current I as shown in graphic 1 which depicts the behavior of the channel current I as a function of the gate voltage VGS referenced respect to source keeping the drain-source voltage VDS fixed for each curve. Such curve is obtained considering the contribution of 4 energy sub-bands.



Graphic 1 IDS vs IGS with the contribution of 4 sub-bands, when VDS=0.2-1.1V

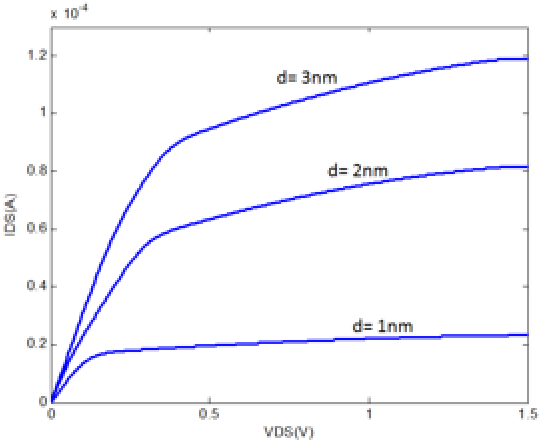
In the case of VGS=0V, the contributions of drain and source are identical but in opposite directions so the channel current is , however when VGS is positive there is an unbalanced contribution with a reduction in drain contribution and it leads to a effective channel current different to zero which is enhanced with increasing of VDS as it can be seen in graphic 1.



Graphic 2 IDS vs VDS with the contribution of 3 sub-bands, when VGS=0.1V, 0.3V, 0.5V, 0.7V.

Besides it is possible to observe that VGS modulation would make a significant variation on carrier transport, it is not the same situation for VDS potential which only increments the inyection of charge carriers through barriers at source and drain regions such barriers have their energy levels height determined by the VGS applied potentials. According to graphic 2, the channel current IDS suffers important increments only in a small range of VDS and so it tends to increment slowly being more significant such increments as the number sub-bands is greater.

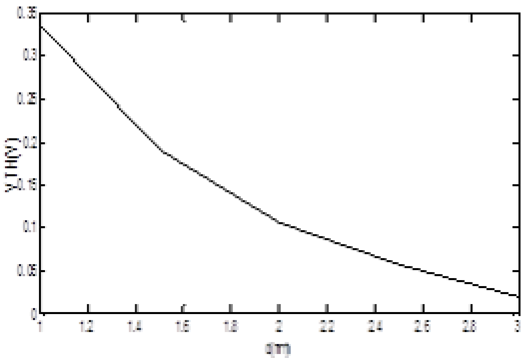
Many of the properties of CNTs are determined from the geometry of the nanotube, so it is not really surprising the big influence of nanotube diameter in the current value. It is also possible to see, that this behaviour is related with the reduction of the bandgap, which can be determined in a direct way from the value of CNT diameter as has been demonstrated that [1].



Graphic 3 IGS vs IDS with the contribution of 4 sub-bands, when VGS=0.6 V, d=1nm, 2nm, 3nm

Graphic 3 shows the behavior of channel current in the CNTFET considering three different CNT diameters, as it is shown the current is higher according as the diameter is greater such behavior is expected since the Eg is smaller the diameter is greater and the reduction of the Eg favors the transition of electrons from the valence energy band to conduction band in the CNT and so the electron population is enhanced in the sub-bands and it yields a major current in the channel. Another important parameter which determines the threshold of the channel current and is linked to the CNT diameter is the threshold voltage, which can be expressed in terms of the diameter in the next equation [3]

$$V_{TH} = 0.91 - 0.81d + 0.27d^2 - 0.033d^3 \tag{8}$$



Graphic 4 VTH for diferent CNT diameter values

Graphic 4 exhibits how this parameter is behaved as a function of the CNT diameter, so in general for a bigger value of the CNT diameter VTH will decrease its value monotonically. The increment in the CNT diameter reduces the CNT Eg and it is required a lesser surface potencial to generate transitions of electrons into the sub-bands in the CNT.

Conclusions

One of the most outstanding characteristics is the clear dependence of the electrical characteristics of the CNTFET on the CNT diameter and their sub-bands number, which indicates that there should be a special interest of controlling these values in the synthesis procedures. Another interesting observation deduced from this work is that the bigger contribution to the channel current value will depend on the first sub-bands with important imcrements in the current as increasing VGS values and small variations when increasing theVDS values.

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