A SIMPLE I-V MODEL OF CARBON NANOTUBE FIELD EFFECT TRANSISTORS

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ABSTRACT
In this paper we present a simple model of Carbon Nanotube Field Effect Transistors (CNTFETs), whose main objective is to obtain a very good agreement between measured and simulated I-V curves through a best-fitting procedure, particularly in the knee and saturation regions. To verify the accuracy of the model, the results have been compared with those of experimental data and of a numerical model online available.

KEYWORDS: *Nanoelectronic Devices, Nanotechnology, Carbon Nanotube Field Effect Transistors, Modelling, Output and Transfer Characteristics.*

I. INTRODUCTION

The aggressive scaling of CMOS led to higher and higher integration density in microcircuits, lower power consumption and increased performance.
However, the scaling down will eventually reach its limit. As device sizes approach the nanoscale, new opportunities arise from harnessing the physical and chemical properties at the nanoscale.
Carbon Nanotubes (CNT) are considered as the most promising carbon nanostructures, and, in particular, the Carbon NanoTube Field Effect Transistors (CNTFETs) are a new kind of molecular device, using a carbon nanotube as channel. Today CNTFETs are regarded as an important contending device to replace conventional silicon transistors [1].
As it is known [2], the carbon nanotubes consist in a hexagonal mesh of carbon atoms wrapped in cylinder shapes, some time with closing hemispherical meshes on the tips.
These tubes could have various radii, lower than two nanometers and, since they could be extended also several millimeters, they have a huge length/diameter ratio making them unidimensional structures. Depending on the mesh torsion, denoted as *chirality*, electronic band structure of CNT changes, band gap may appear making them semiconductors, or may not appear, making them conductors. Furthermore the CNT behaviour as semiconductor has an energy gap inversely proportional to their radius.
Among carbon nanotube FETs, conventional CNTFETs or C-CNTFETs, with heavily doped source and drain contacts, show the best performances in terms of "on-off" ratio currents and subthreshold swing.
About modelling issues, the research on CNTFETs is still at an early stage [3-10]. Most of the models available in literature are numerical and make use of self-consistency and therefore they cannot be directly implemented in CAD tools, such as SPICE or VHDL-AMS.
In this paper we propose a simple I-V CNTFET model whose main objective is to obtain a very good agreement, particularly in the knee and saturation regions, between measured and simulated I – V characteristics through a best-fitting procedure,.
The accuracy of the model is verified by the very low error measure between the measured curves [11] and those obtained from the proposed model. Moreover the model has been also compared with data obtained from simulator online available [12].
The presentation is organized as follows. Section 2 gives a brief description of CNTFETs. The proposed model is presented in Section 3, while the comparison between measured and numerical

results and those of the proposed model are given in section 4. The conclusions are described in Section 5.

II. CARBON NANOTUBE FIELD EFFECT TRANSISTORS

The smaller and smaller scaling of electronic devices approaches the time when the diffusion regions of transistors will be so close that the channel will be few atoms thick and gate oxide so thin that the charge will tunnel through it: this will be the ultimate size and performance of silicon-based devices.
The Carbon NanoTubes have been identified as an excellent choice for next generation of field-effect transistors, which maintain the operating principles of the currently used devices, but replace the conducting channel with carbon nanomaterials such as one-dimensional (1D) CNT or two-dimensional (2D) graphene layers.
These new devices have molecular building block not coming from lithography and, along with these devices, molecular electronics will change the equation in our tool box, we will drop out well known partial differential equation for charge diffusion and we will use quantum mechanic to describe electrons, holes, atoms, molecules and photons. In coming years we will gain new tools from chemistry and physics, new sophisticated mathematical tool to face probability amplitude waves.
Carbon NanoTube Field Effect Transistors (CNTFETs), as already written, are FETs using a carbon nanotube as channel, and are regarded as an important contending device to replace conventional silicon transistors [1]. As it is known, the carbon nanotubes consist in a hexagonal mesh of carbon atoms wrapped in cylinder shapes, some time with closing hemispherical meshes on the tips. Since they could be extended for several millimeters, they have a huge length/diameter ratio making them unidimensional structures (1-D). Moreover an important characteristic of CNT is mesh torsion, denoted as *chirality*, which has a strong influence on the CNT behaviour. Depending on their torsion, electronic band structure changes, band gap can appear making them semiconductors, or cannot appear, making them conductors. Furthermore the CNT behaviour as semiconductor has an energy gap inversely proportional to their radius [2].
In particular, in this paper, we have considered the conventional CNTFETs, denoted as C-CNTFETs, with heavily doped source and drain contacts, because these devices show the best performances in terms of "on-off" ratio currents and sub-threshold swing.
Fig. 1 shows a 3D representation of a C-CNTFET, whose conduction behaviour is similar to a common MOSFET..

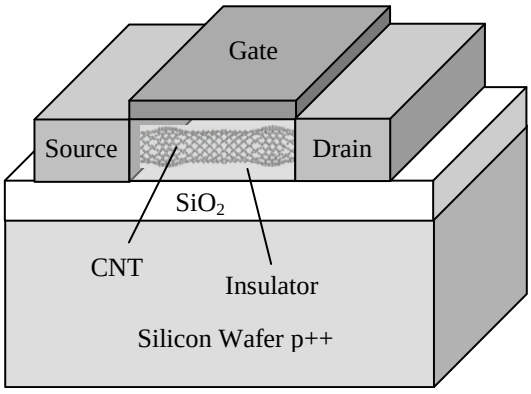

Figure 1. 3D representation of a C-CNTFET.

III. THE PROPOSED MODEL

The CNTFET model that we propose has been implemented with the following aims:

1. to improve the accuracy of modelled I-V curves, in particular in the knee and saturation regions;
2. to give the device source-drain current as a function of external voltages, as seen at the device gates, by-passing the very difficult measurement of parasitic resistances for the I-V characterisation.

3. to use empirical parameters to be extracted by a quick and accurate procedure, the initial estimation of empirical parameters being performed referring to measured I-V curves and to physical considerations, making univocal, fast and easy the extraction of the best fitting parameter set.

The proposed model has the following expression:

$$I_{ds}(V_{ds}, V_{gs}) = I_{dss}\left[\left(1-\frac{V_{gs}}{V_t}\right)^N\right]\left[\tanh(aV_{ds})\right]^M \quad (1)$$

where I_{dss} is the maximum saturation drain current, which is not an empirical parameter,

$V_t = V_{to} + \gamma * V_{ds} * V_{gs}$

is the threshold voltage, V_{to} is the threshold voltage at zero bias, γ is the threshold voltage shift parameter, and

$$N = N_0 + N_1 V_{gs} + N_2 V_{gs}^2 + N_3 V_{gs}^3 \quad (2a)$$

$$\alpha = a_0 + a_1 V_{gs} + a_2 V_{gs}^2 + a_3 V_{gs}^3 \quad (2b)$$

being V_{ds} the drain-source voltage and V_{gs} the gate-source voltage.

Equations (2) allow the third order dependence of N and α on the bias conditions, improving the fitting in the linear, knee and saturation regions. Moreover, the M parameter improves the fitting in the knee region, modifying here the behaviour of hyperbolic tangent function.

The voltages in eqn. (1) are external, i.e. measured at the device external terminals. In this way it is possible to overcome the problem of measurement of the parasitic resistances, thus making easier the parameter extraction procedure and the use of the model for circuit design. If the complete DC device characterisation requires the resistances to be determined, the linear approximation can be used for them without affecting the I-V model accuracy.

The extraction of the 11 empirical parameters has been obtained by an appropriate optimisation routine, that minimizes the root-mean-squared (RMS) difference between the function and the simulation results.

The empirical parameters are extracted with high accuracy, not all at once but by dividing the set of 11 parameters in two batches.

First, the coefficients V_{to}, γ and N_i are extracted by considering the I- V characteristics in the saturation region. The initial value of the parameter γ has been assumed equal to $0.03V^{-1}$ based on measurements of the threshold voltage as a function of bias condition. The initial value of the coefficient N_0 has been assumed to be 2, while the other coefficients N_i (i = 1, 2, 3) are zero, since N does not depend on the bias conditions in a first approximation.

The parameters M and a_i, coefficients of α characterising the device behaviour in the linear region, are calculated minimising the error between measured and modelled current values in the entire range of measurements, i.e. in the linear and saturation regions.

To extract these parameters an initial approximation for M is assumed, i.e. M = 1. In fact the parameter M is only a fitting parameter, without any physical meaning, which modifies the hyperbolic tangent shape especially in the knee region, so allowing the best fit with measured current values to be obtained. Therefore, evaluating as a first approximation M = 1 does not account for this parameter.

The initial values of coefficients a_i can be calculated following two approaches based on two physical approximations. Both approaches derive from the observation that the hyperbolic tangent function approaches to unity when its argument is large enough, i.e. $\alpha * V_{ds} \geq 6$. Moreover, an approximated physical analysis of the device behaviour in the saturation region suggests that the current is almost constant and, therefore, in the present model in the saturation region the hyperbolic tangent function

must approach unity. This means that, for an approximate estimation of coefficients a_i, one can impose that $\tanh(\alpha * V_{dsat}) \rightarrow 1$.
According to these considerations, to estimate coefficients, a rough, but useful approximation involves neglecting the dependence of V_{dsat} on V_{gs}; then one can estimate V_{dsat} by data measured at $V_{gs} = 0$ V as the value of V_{ds} corresponding to the maximum current, and subsequently to estimate

$a_0 = 6/ V_{dsat}$ $a_1 = 0$ $a_2 = 0$ $a_3 = 0$.
The thermal dependence of DC characteristics, which may be approached by the calculations of the thermal gradient inside the device and drain-source current I_{ds}, since the thermal field depends on the consumed power, has not been considered in this paper because at the present, in literature, there are not yet the measured I-V static characteristics of CNTFETs at different temperatures, absolutely necessary to compare the modelled values.

IV. DISCUSSION OF THE SIMULATIONS

Firstly, we have extracted the fitting parameters, i.e. V_{to}, γ, N_o, N_1, N_2, N_3, a_o, a_1, a_2, a_3, M by minimizing a squared error function within the required tolerance (typically 10^{-4}). This fitting parameter extraction was performed in two steps: in the first, only the parameters V_{to}, γ, N_o, N_1, N_2, N_3 involved in saturation region are extracted. In the second step, the remaining parameters characterizing the linear region, i.e. a_o, a_1, a_2, a_3, M, are obtained.
The strong improvement of accuracy is fundamentally due to the third-order dependence of α and N on voltage V_{gs} and to the dependence of V_t on V_{gs}. Moreover, the model parameter extraction procedure is fairly quick and unique due to the close estimation of their initial values to start the extraction routine. Finally, the CPU execution times for the model parameter extraction and for the model calculation are reasonably small.
Then we have plotted the output and transfer curves for a C-CNTFET, whose technological characteristics are reported in [6] and in [13].
Fig. 2 shows the $I_{DS} - V_{DS}$ characteristics (denoted by continuous lines) of numerical simulations according to our procedure and the experimental ones [11] (denoted by +).
As shown in Fig.1, we have obtained a very good agreement between measured and modelled data in terms of I_{ds} versus V_{ds}.
The calculation error has been very low, |E| = 1.71 mA, with relative percentage of 4.4%.
Moreover the CPU calculation time was very short, 0.03 s, by using a 2.4 GHz compatible PC.

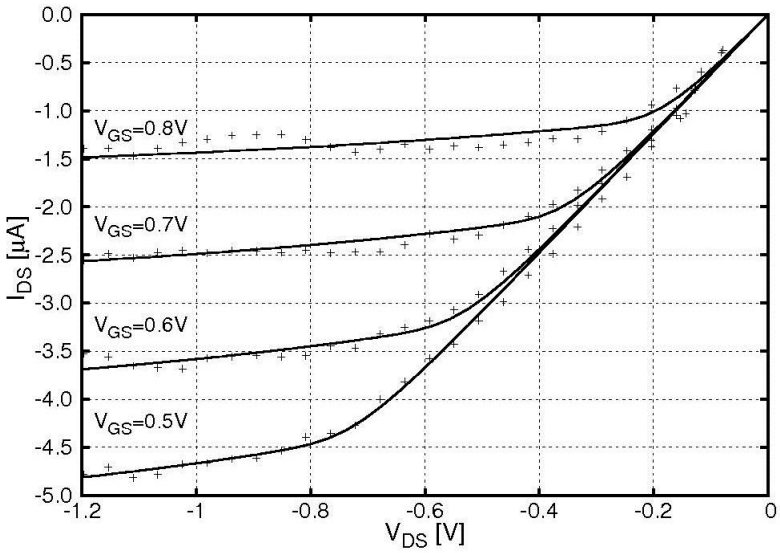

Figure 2. Simulated $I_{DS} - V_{DS}$ characteristics (denoted by continuous lines) and experimental $I_{DS} - V_{DS}$ characteristics [11] (denoted by +).

The calculation error is low also for the transfer characteristics, as it is possible to see from Fig. 3, which compares the modelled $I_{DS} - V_{GS}$ characteristics (denoted by continuous lines) and the experimental ones [11] (denoted by +, *, triangles, etc., for any value of V_{DS}).

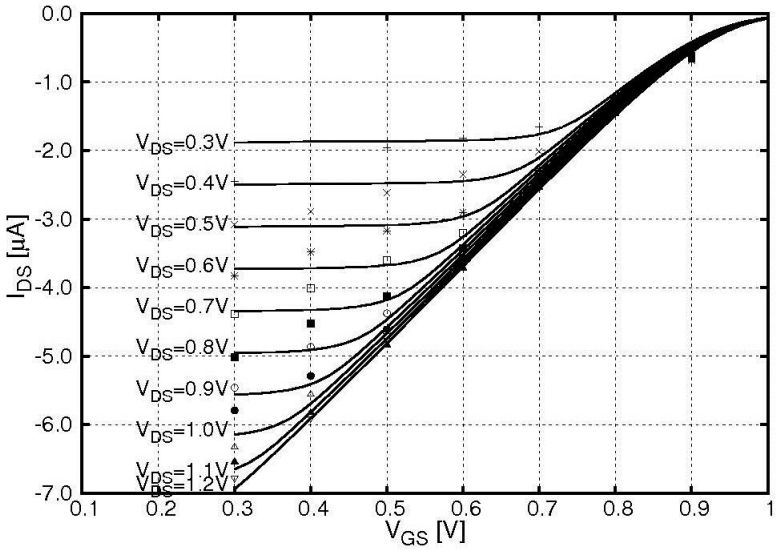

Figure 3. Simulated $I_{DS} - V_{GS}$ characteristics (denoted by x) and the experimental ones [11] (denoted by +, *, triangles, etc., for any value of V_{DS}).

At last, in Fig. 4 we have shown the simulated $I_{DS} - V_{GS}$ characteristics (denoted by x) by our model and the numerical $I_{DS} - V_{GS}$ characteristics (denoted by +) [12].

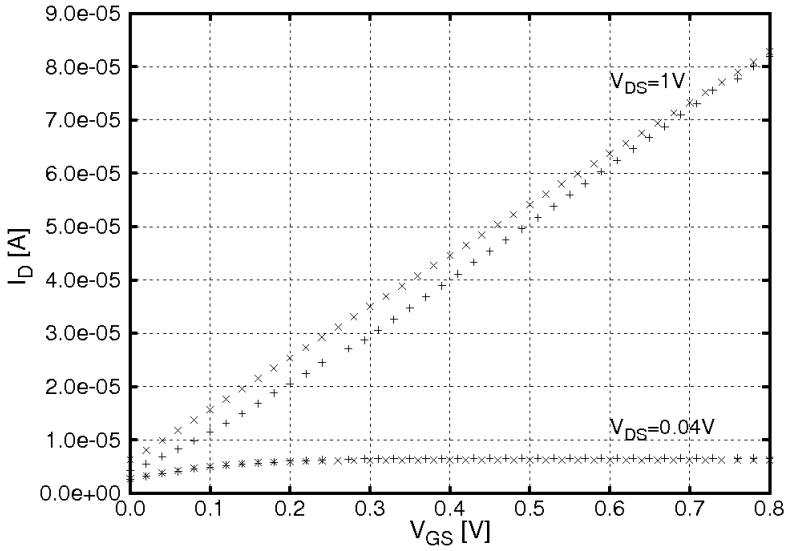

Figure 4. Modelled $I_{DS} - V_{GS}$ characteristics (denoted by x) and numerical $I_{DS} - V_{GS}$ characteristics [12] (denoted by +).

These results have been obtained calculating the root mean-square errors between our model and the numerical ones online available, obtaining small values, of the order of 1% or lower, with a CPU calculation time much more low. In this way we can assert that there is an high improvement in accuracy of our model.

V. CONCLUSIONS AND FUTURE DEVELOPMENTS

In this paper we have proposed a simple model of CNTFETs, whose main aims have been to improve the accuracy of modelled I-V curves, in particular in the knee and saturation regions, to give the device source-drain current as a function of external voltages, by-passing the very difficult

measurement of parasitic resistances for the I-V characterization and to use empirical parameters to be extracted by a quick and accurate procedure.
The initial estimation of empirical parameters are performed referring to measured I-V curves and to physical considerations, making univocal, fast and easy the extraction of the best fitting parameter set. The extraction of the empirical parameters of the model has been obtained by an appropriate optimization routine, that minimizes the root-mean-squared difference between the function and the simulation results.
In particular we have utilized the proposed model in order to reproduce the measured I - V characteristic curves for a C-CNTFETs. The calculation error has been very low, |E| = 1.71 mA, with relative percentage of 4.4% and a CPU calculation time of about 0.03 s, by using a 2.4 GHz compatible PC.
At last the model has been also compared with numerical data obtained from simulator online available and the root mean-square errors between our model and the numerical ones has been of the order of 1% or lower, with a CPU calculation time much more low.
In the future, in order to validate the implementation of the proposed CNTFET model, we will utilize it, both in Verilog-A and in SPICE simulators, to design typical analogue circuits and logic blocks.

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