A MODULAR APPROACH FOR THE SIMULATION OF A PARAMETER DEPENDENT SWCNT INTERCONNECT

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Abstract–*A simple approach based on a commercial package like PSIM® is used for simulating the behaviour of an InterConnect (IC) based on a Single Wall Carbon NanoTube modelled by an equivalent Transmission Line (TL). The simulator is also employed for computing all the per unit length parameters of the TL in terms of the geometrical, physical and thermal dependencies of the considered structure. An equivalent two port circuit is developed that can be used for time domain analysis of the nano ICs, including also the interesting feature of the evaluation of the performances ranges occurring in presence of characteristic parameter variations.*

Keywords: *nanointerconnect, parameter dependent, circuital simulation, CNT.*

1. INTRODUCTION

The continuous miniaturization and the increase of the working frequencies and power density of future nano electronics integrated circuits drive towards innovative realizations for on chip interconnections and vias. The actual technology based on copper will no longer satisfy future requirements in terms of electrical and electromagnetic performances [1]. In fact, it has been shown that at very low cross section the resistance of copper, due to grain boundary scattering, surface scattering and the presence of the very resistive diffusion barrier layer [2] may be affected by steep increase, thus hindering the interconnect speed and reliability [3]. In particular, the waveform of the output voltage V_2 in the schematic nano-IC shown in Fig. 1a, would be characterised by a reduced amplitude and by an unacceptable time delay with respect to the input V_1. For these reasons, the use of Carbon NanoTubes (CNTs), characterised by high thermal and electrical conductivity, very large current carrying capability, remarkable thermal and mechanical stability [1]-[2], has been proposed for the realization of future interconnects [3]. Research efforts are aimed at the development of simulation models for the analysis and design of the CNT-based nano-IC [4] and at evaluating the influence of the production technology and constraints on electromagnetic performances [5]. In this paper the study of the behaviour of a CNT-based nano- IC is obtained by modelling it through a Transmission Line (TL) (Fig. 1b) which is simulated by using a widely adopted circuit simulator like PSIM® [6]. The considered circuit is formed by N cells simulating an IC section of length *dx*: the resistance, inductance and capacitance (R',L',C') of each cell are obtained from the corresponding per unit length (p.u.l.) parameters which, in turn, are linked to the physical and geometrical properties of the CNT [7]. The calculation of such p.u.l. parameters is achieved by using a peculiar feature of PSIM® that realizes, through suitable circuital blocks, the evaluation of the mathematical functions relating the properties to the circuital parameters [8]. Hence, and this represents a distinctive aspect of this paper, the simulator is used for a twofold aim: the evaluation of the TL parameters and the study of the time evolution of the CNT-based IC when such parameters are assumed as variable.

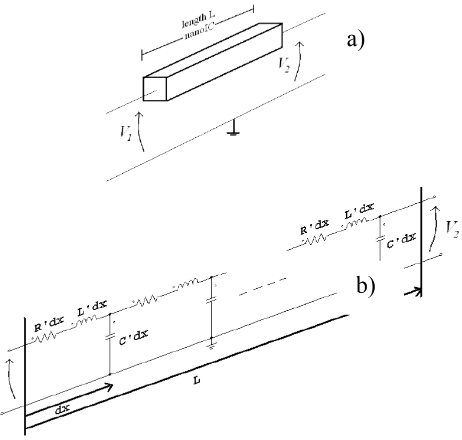

Fig. 1. Schematic nanointerconnect (a) and its equivalent Transmission Line model (b).

2. MODEL AND METHODS

A Single Wall CNT (SWCNT) above a perfectly conducting ground plane shown in Fig.

2 is assumed as a representative structure of a CNT-based nano-IC.

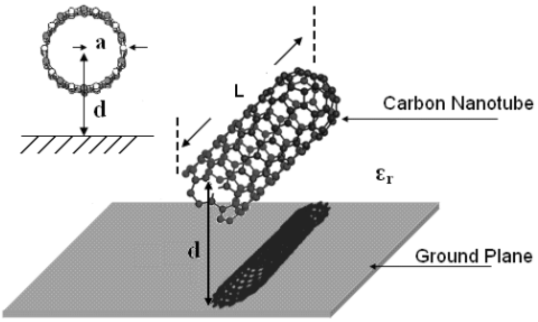

Fig. 2. SWCNT over a perfectly conducting plane.

The nano-IC length, L, the distance between the centre of the SWCNT and the ground, d, the radius of the SWCNT, a, the electron mean free path in the SWCNT, l_{mfp}, and the relative permittivity of the surrounding medium ε_r are the parameters which, due to tolerances associated to the technological production process or to measurements uncertainties, are considered variable. They are directly connected to the values assumed by the p.u.l. parameters of the TL circuit modelling the considered structure [7], [9].

$$R' = \begin{cases} \dfrac{h}{4\cdot e^2}\cdot\dfrac{L}{l_{mfp}} & \text{with} \quad L > l_{mfp}, \\ \dfrac{h}{4\cdot e^2} & \text{with } L \le l_{mfp} \end{cases} \tag{1}$$

$$L' = L'_m + \frac{L'_K}{4} = \frac{\mu_0}{2\pi}\ln\frac{2d}{a} + \frac{1}{4}\cdot\frac{h}{2e^2\upsilon_F} \tag{2}$$

$$C' = \frac{4C'_q C'_e}{4C'_q + C'_e} = \frac{4\cdot\dfrac{2e^2}{h\upsilon_F}\dfrac{2\pi\varepsilon}{\ln\left[\dfrac{d}{a}+\sqrt{\left(\dfrac{d}{a}\right)-1}\right]}}{4\cdot\dfrac{2e^2}{h\upsilon_F}+\dfrac{2\pi\varepsilon}{\ln\left[\dfrac{d}{a}+\sqrt{\left(\dfrac{d}{a}\right)-1}\right]}} \tag{3}$$

In particular, the p.u.l. damping resistance R', the total p.u.l. inductance L' and capacitance C' of the nano-TL are given respectively by in which L'$_k$ and C'$_q$ are the p.u.l. kinetic inductance and p.u.l. quantum capacitance [2], L'$_m$ and C'$_e$ are the p.u.l. effective magnetic inductance and electrostatic capacitance of the structure, h is the Plank constant, e is the electron charge, $\upsilon_F = 8*10^5$m/s is the Fermi velocity, μ_0 the magnetic permeability of the air and $\varepsilon=\varepsilon_0\varepsilon_r$ is the dielectric constant of the medium.

Hence the p.u.l. parameters are function of the considered variable parameters, $f_i = f_i\left(d,\ a,\ l_{mfp},\ \varepsilon_r\ L\right)$ with $i \in \left\{R', L', C'\right\}$, that in PSIM® can lead to represent the system in Fig. 2 by means of the two port component depicted in Fig. 3.

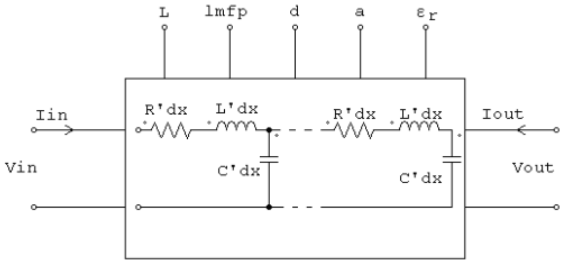

Fig. 3. Equivalent two-port modelling the TL cells.

The end user of the proposed approach can make the simulations of a SWCNT-based nano-IC by a two step procedure: the circuital computation of the p.u.l. parameters and the adoption of such values for the lumped parameters in the circuit of Fig. 3. First of all the blocks linking in a circuital way the physical and geometric properties to the p.u.l. parameters are constructed. Each input and the corresponding outputs are indicated by means of a label and considered as a voltage, whereas every constant appearing in the expression is treated as a dc voltage source. The different blocks are illustrated in Fig. 4. The p.u.l. resistance R' is a function of the IC length L and the electron mean free path, $R' = f_R\ (l_{mfp}\ L)$. In the corresponding block a control circuit performs the choice associated to the considered l_{mfp} by opening/closing the switch that enables the correct value. The p.u.l. L' is a function of the distance between the ground plane and the SWCNT and of the CNT radius, $L' = f_L\ (d,\ a)$, whereas the p.u.l. capacitance C' is a function of the previous parameters and the dielectric permittivity of the medium $C' = f_c\ (d,\ a,\ \varepsilon_r)$. In particular, the expression of the electrostatic capacitance can be simplified for the condition in which d/a>>1:

$$C'_e = \frac{2\pi\varepsilon}{\ln\left[\dfrac{d}{a}+\sqrt{\left(\dfrac{d}{a}\right)-1}\right]} \cong 2\pi\varepsilon\left(\ln\frac{2d}{a}\right)^{-1}$$

Since no input parameter is time dependent, the simulation of the "circuits" in the second column of Fig. 4 instantaneously furnishes the values that must be adopted as lumped parameters in the network of Fig. 1b for each input set.

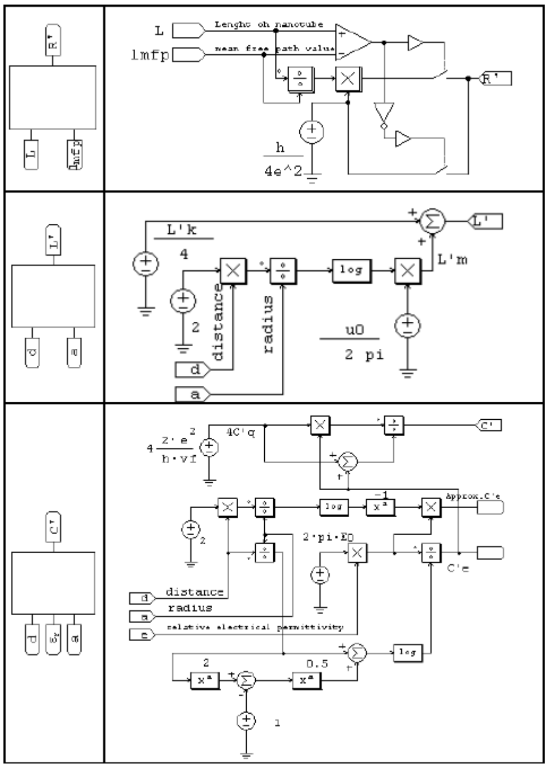

Fig. 4. PSIM® sub-circuits linking the physical and geometrical properties to the TL p.u.l. parameters.

By connecting the "total" equivalent two-port circuit of Fig. 3 to an input and output devices, all the facilities of the PSIM® environmental can be easily performed in order to evaluate the behaviour of a nano-IC based on a SWCNT.

3. RESULTS

The circuit depicted in Fig. 5 comprising a driver and a load with their parasitic parameters is adopted for performing the numerical simulation of the considered nano-IC.

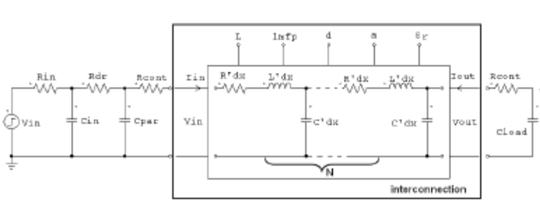

Fig. 5. PSIM® circuit adopted for simulating The nano-IC.

In particular here we have considered a driver with a resistance R_{dr}=96Ω, an input capacitance C_{in} equal to the parasitic capacitance C_{par} of 64fF and a load with a capacitance C_{load}=91fF. In this scheme also the CNT/metal contact resistance, R_{cont} of 61Ω is considered [4].

The nano TL is here approximated by N=5 cells of length dx=L/N. By considering local interconnects with a variable length $L\in\{0.1,1,10\}$μm, a SWCNT of radius $a\in\{0.5,1,1.5\}$nm, at 100nm of distance by the perfectly conducting ground plane, with a mean free path of 1μm in a low-k medium with a relative permittivity of 1.5, the p.u.l. TL parameters assume the values reported in Table 1, computed by performing the simulation of the three circuits depicted in Fig. 4.

Table 1. Computed p.u.l. values of the TL parameters: adopted input parameters d=100nm, lmfp=1μm, εr=1.5.

L[μm]	*a*[nm]	*R'*[kΩ]	*L'*[mH]	*C'*[pF]
0.1	0.5	6.45	4.0353	0.1344
	1	6.45	4.0352	0.1513
	1.5	6.45	4.0351	0.1634
1	0.5	6.45	4.0353	0.1344
	1	6.45	4.0352	0.1513
	1.5	6.45	4.0351	0.1634
10	0.5	64.55	4.0353	0.1344
	1	64.55	4.0352	0.1513
	1.5	64.55	4.0351	0.1634

By using the values of Table I for the p.u.l. components in Fig. 5 and by applying an ideal unitary step voltage input, the simulations of the corresponding circuits for different length of the nano-IC show characteristic behaviours of the output voltage, as illustrated in Figs. 6-8.

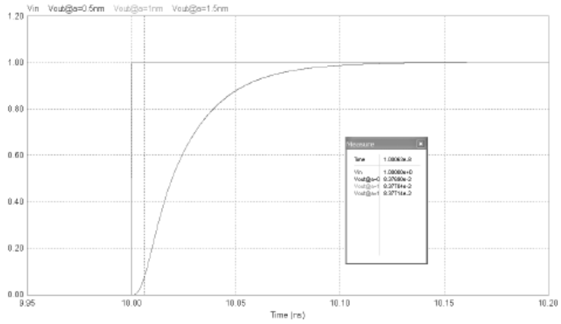

Fig. 6. Time behaviour of the input and output voltage for three different CNT radius with L=0.1 μm.

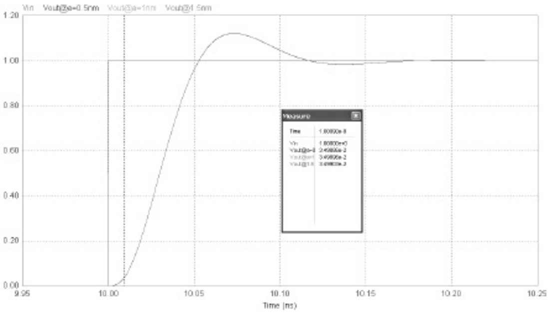

Fig. 7. Time behaviour of the input and output voltage for three different CNT radius with L=1 μm.

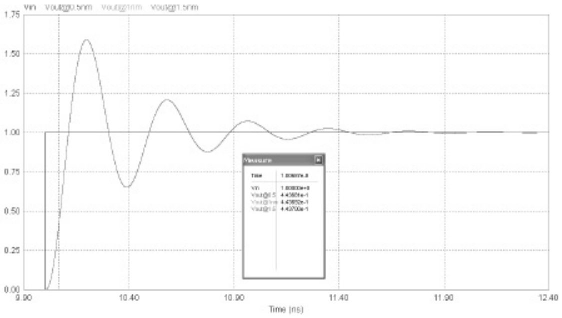

Fig. 8. Time behaviour of the input and output voltage for three different CNT radius with L=10 μm.

In particular very short interconnects assume a quasi RC behaviour (Fig. 6) whereas, with the increase of the length, an underdamped dynamics becomes visible (Fig. 7 and Fig. 8). The overshoot in the output voltage increases, together with the time constant, going from local (1μm) to intermediate (10μm) nano-IC. Furthermore, as shown by the overlapping dynamics, the output voltage is not influenced by the CNT radius.

Only in the first part of the responses a difference on the third/fourth significant digit is appreciable as highlighted by the measurements shown in the inset on the same figures. An analysis in frequency domain is also possible.

The fast and simple computation of the response of the circuit allows to easily perform the optimization of relevant quantities (such as the 50% delay time) of the SWCNT-based interconnect in presence of different physical and geometric characteristics. A parameter sweep can be included in the procedure in order to make such a sensitivity analysis fully automatic.

4. CONCLUSIONS

The calculation of the p.u.l. parameters of an equivalent TL simulating a a SWCNT-based nano-IC is carried out in PSIM® by implementing blocks in which the mathematical functions, relating the physical and geometric properties to the circuital parameters, are evaluated. Such blocks can be easily integrated in the same environment in a circuit, comprising also the nano-IC driver and load, in order to perform simulations allowing both time and frequency domain analysis. A significant dependence of the dynamics on the length of the nano-IC and a substantial independence from the CNT radius has been evidenced. The easy availability of the circuit response for different configuration/materials of the nanoIC can be exploited in order to perform the nanoIC design and optimization. Further efforts are now underway in order to consider also nano-IC based on bundles of SWCNT or Multi Wall CNT.

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