The Body Doping Concentration Effects on the CNTFETs Characteristics

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***Abstract*— This paper presents the effects of body doping concentration on a carbon nanotube field-effect transistor (CNTFET) with symmetrical coaxial geometry structure, that transistor has a wrapped gate dielectric around the nanotube. At first, Gordon Moore's law is expressed briefly. Then, the limitations and problems after 10nm channel lengths of the traditional metal-oxide-semiconductor field-effect transistors (MOSFETs) scaling are introduced and the structure of carbon nanotube field-effect transistor as a solution for limitations is illustrated. The simulation process is performed, then the effect of body doping concentration is investigated on the current-voltage characteristics, energy profile and electron density of transistor. The simulation is based on a self-consistent solution of the two dimensions Poisson equation and Schrodinger solver. Results show that with increasing body doping concentration level, the transistor output current, energy profile and electron density of transistor will increase and on/off current ratio will decrease.**

***Index* Carbon Nanotube Field Effect Transistor (CNTFET); body doping; self-consistent solution; Schrödinger equation.**

I. Introduction

In 1965 Gordon Moore predicted that the number of transistors on a chip will double every 18 months. In other words, the dimensions of devices will decrease to half [1]. Scaling down of devices is necessary for advanced electronic technology. Traditional MOSFETs have many important limitations and problems after 10nm channel lengths [2]. According to ITRS, MOSFETs will reach their limits in 2020 [3]. The limitations are electron tunneling through short channels and thin insulator films, the associated leakage currents, passive power dissipations, short channel effects, increasing cost of the fabrication process, variations in device structure and doping process. Therefore new inventions are needed [4]. The semiconductor industry is looking for new materials for replacing silicon in electronic devices [5]. One of the most promising building blocks for the future of nanoelectronic devices is Carbon Nanotubes (CNT).

Iijima discovered Carbon nanotubes (CNTs) as a by-product in 1991 in NEC Corporation [6]. CNTs are cylindrical of carbon sheets that have many numbers of unique features and special properties such as high electrical conductivity, heat conductivity, metallic or semiconducting behavior, ballistic electron transport, huge current carrying capacity, high mobility, compatibility with high dielectric constants (K) and small diameters that are suitable for the basic building blocks in future nanoelectronic applications. In order to use this excellent property of CNTs, scientists have fabricated Carbon Nanotube Field Effect Transistors (CNTFETs) based on single-walled semiconducting CNTs as channel material, that fabricated for the first time in 1998, hence CNTFETs are one of the novel nanoelectronic devices that overcome MOSFETs limitations. In order to study the performance of CNTFETs, the self-consistent solution of the Poisson and Schrodinger equations is used, then the body doping concentration effect on the CNTFETs characteristics has been investigated [7].

II. Two-Dimensional Simulation of Carbon Nanotube Field-Effect Transistors

In this section, electron transport simulation in a semiconducting nanotube that using in the CNTFET structure is described. For the accurate simulation of CNTFETs self-consistent solution of the Poisson and Schrodinger equations is used. The CNTFET with Coaxial geometry structure is used in this research, the transistor has a wrapped gate dielectric around channel length. Fig.1 shows the structure of CNTFET that is used in this work.

the nanotube. The reason for this kind of structure selection is the cylindrical nature of CNTs. This structure provides the best channel controlling by gate field, as sequence the minimum

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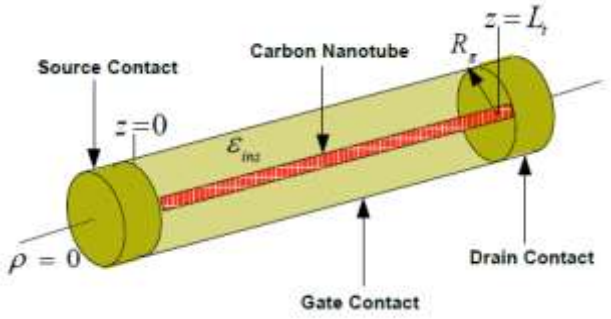

Fig.1: Coaxial CNTFET model geometry.

Drain and source contacts have the same radius and length with gate contact. The nanotube in this device structure is surrounded by an insulator with relative permittivity ε_{ins}. The source and drain contacts terminate the ends of the device. R_g is the gate radius, R_t is nanotube radius, the insulator thickness $t_{ins}=R_g-R_t$ and the nanotube length is L_t. In this system due to its symmetrical geometry, Poisson's equation, restricted to just two dimensions [8]–[10].

$$\frac{\partial^2 V}{\partial \rho^2}+\frac{1}{\rho}\frac{\partial V}{\partial \rho}+\frac{\partial^2 V}{\partial z^2}=-\frac{Q}{\varepsilon} \quad (1)$$

Where the Q is charge density and V(ρ,z) is the potential within the outer cylinder. The charge distribution on the surface of the nanotube is obtained by solving the Poisson equation coupled with the time-independent Schrödinger equation:

$$\frac{\partial^2 \Psi}{\partial z^2}=-\frac{2m^*}{\hbar^2}(E-U)\Psi=-K^2\Psi \quad (2)$$

Where Ψ(z,E) is the wave function of a carrier with total energy E and effective mass m^*, traveling in a region with local effective potential U(z). (1) solving is required with Q=Q(V). Convergence for this non-linear system is achieved when:

$$V_{k+1}=V_k-\alpha L^{-1} r_k \quad (3)$$

$$r_k=LV_k+Q(V_k) \quad (4)$$

Where rk is the residual of the k-th iteration, α is a damping parameter, and L represents the differential operator allowing (1) to be written as:

$$LV=-Q \quad (5)$$

The energy of the nanotube vacuum level is calculated by:

$$E_{vac}(z)=-qV_{GS}(z) \quad (6)$$

The potential of electrons and holes in the nanotube are given by (7) and (8).

$$U_e(z)=E_{vac}(z)-\chi_{CN} \quad (7)$$

$$U_h(z)=-U_e(z)+E_g \quad (8)$$

Where Eg is bandgap of nanotube and χ_{CN} is electron affinity. The charge density is calculated by:

$$Q=\frac{q(p-n)}{2\square}\frac{\delta(\rho-R_t)}{\rho} \quad (9)$$

Where δ(0)/ρ is Dirac delta function in cylindrical coordinates, p and n are electron and hole density that is achieved from the Schrodinger equation. The solution of Schrodinger equations is performed with using the scattering-matrix method. The total of the system is divided into N equal sections. For each section, the electron wave function is introduced by:

$$\Psi_i=A_i e^{ik_i z}+B_i e^{-ik_i z} \quad i=1,2,\dots,N \quad (10)$$

Where k is wave vector, A, B are wave function amplitude. Boundary conditions between i, i+1 sections of the system are:

$$\Psi_i=\Psi_{i+1} \quad (11)$$

$$\frac{\partial \Psi_i}{\partial z}=\frac{\partial \Psi_{i+1}}{\partial z} \quad (12)$$

According to scattering-matrix theory, the relationship between $\begin{bmatrix}A_i\\B_i\end{bmatrix}, \begin{bmatrix}A_{i+1}\\B_{i+1}\end{bmatrix}$ is:

$$\begin{bmatrix}A_{i+1}\\B_i\end{bmatrix}=S_i\begin{bmatrix}A_i\\B_{i+1}\end{bmatrix} \quad (13)$$

Where S_i is scattering-matrix, Ψ_1 and Ψ_N are wave functions at the source and drain contacts. For simulation, the initial charge density inside the device usually is assumed zero. The electron potential inside the device is achieved by solving Poisson's equation. Then with using the scattering matrix method for solving the Schrodinger equation, the net charge density in the device is computed. Then these results used to solve the Poisson equation again and these steps are repeated until between two steps convergence achieved.

III. SIMULATION RESULTS

In this section, the results of the simulation based on the CNTFET theory described in section 2, is considered. The carbon nanotube used in this CNTFET structure is a zig-zag nanotube with chirality (16,0). The diameter of the nanotube is 0.63nm, and the corresponding bandgap is 0.62eV. Nanotube length is 20nm, also source and drain contacts lengths are 20nm, the dielectric is hafnium with thickness, t_{ins}=2nm, and ε_{ins}=25.

Fig.2 and 3 show the I_{DS}-V_D and I_{DS}-V_G characteristics of CNTFET with mentioned parameters in different body doping concentrations. The Body doping concentration is changed from $N_b=0cm^{-3}$ to $N_b=1.3\times e^9 cm^{-3}$ and results are shown in Fig. 2-7. When the concentration is below than $N_b=1\times e^7 cm^{-3}$, Output characteristics changes are not noticeable. According to simulation results, maximum body doping concentration that we can apply to this CNTFET is $N_b=1\times e^9 cm^{-3}$ When the doping concentration is higher than this value, simulation results are not agreeable.

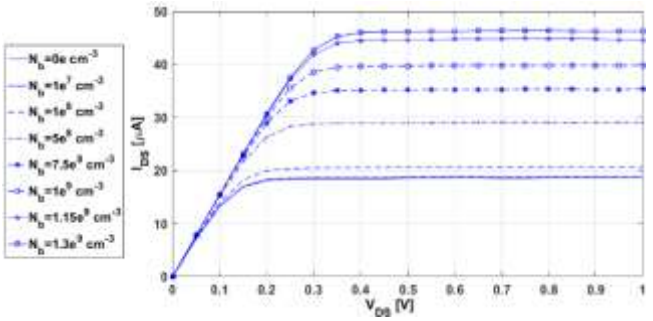

Fig. 2: I_{DS}-V_D characteristics of CNTFET for different body doping concentrations, at V_{GS}=0.5V

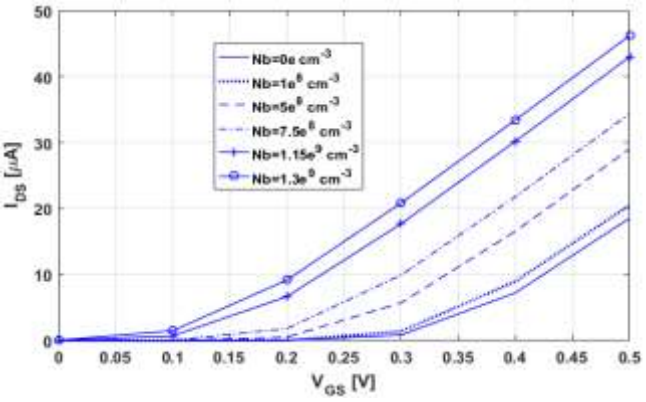

Fig. 3: I_{DS}-V_G characteristics of CNTFET for different body doping concentrations, at V_{DS}=1V

According to Fig.4, with increasing body doping concentration, the output current increases. In this CNTFET structure, there is a barrier region near the source/drain contacts and nanotube channel. These barriers determine the number of electrons entering the channel. The height of barriers is modulated by the body doping concentration. With increasing the body doping level, there is a consequent decrease in the barrier height. Hence, more carriers flow through the channel and output current will increase. In Fig.4, the Output current is shown as a function of body doping concentration.

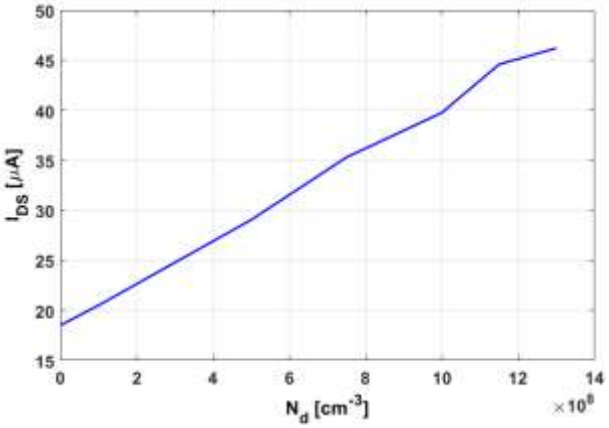

Fig.4: Output current versus body doping concentrations.

According to Fig.5, with increasing body doping concentration, the energy profile of CNTFET increases. More doping concentration allows more propagation in the channel.

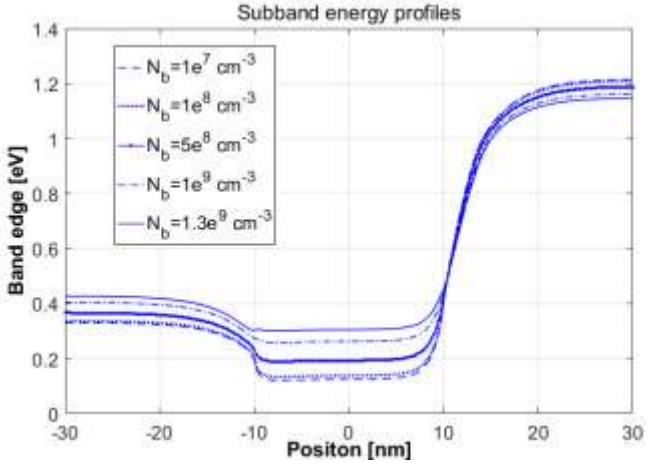

Fig. 5: Energy profile of CNTFET for different body doping concentration at V_{GS}=0.5V, V_{DS}=1V.

According to Fig.6, with increasing body doping concentration, the electron density of CNTFET increases due to increasing drain current.

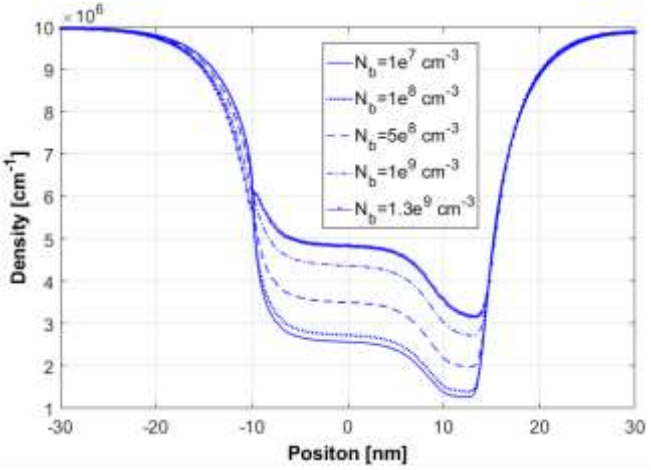

Fig. 6. Electron density of CNTFET for different body doping concentration at V_{GS}=0.5V, V_{DS}=1V

In order to investigate body doping concentration effect on the I_{ON}/I_{OFF} ratio of CNTFET, it is changed in the range of N_b=0cm^{-3} to N_b=1.3×e^{9}cm^{-3} other parameters are constant. The result is shown in Fig.7 with the mentioned parameters with respect to the body doping concentration at V_{GS}=0.5V, V_{DS}=1V for on-state and at V_{GS}=0.0V, V_{DS}=1V for off-state. When the concentration level is below than N_b=1.0×e^{7}cm^{-3} Output characteristics change is not noticeable.

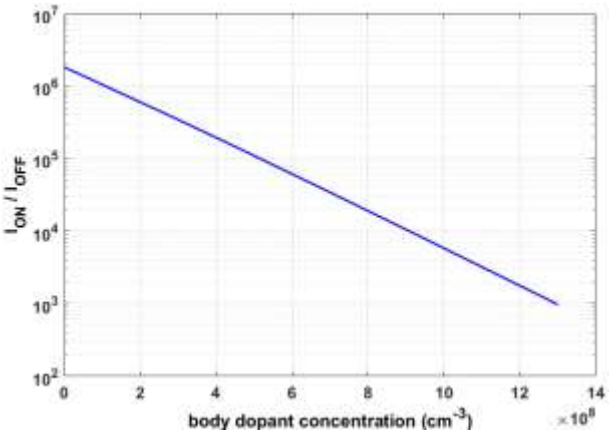

Fig. 7: the I_{ON}/I_{OFF} ratio of CNTFET for different body doping

The maximum body doping concentration level that we can apply to this CNTFET, is N_b=1.3×e^{9}cm^{-3} When the concentration level is higher than this value, simulation results are not agreeable. According to results, with increases in the body doping concentration, on-state and off-state current will increase. But off-state current increment is more than on-state. Therefore the I_{ON}/I_{OFF} ratio decreases. So, body doping concentration has an inverse relation with the I_{ON}/I_{OFF} ratio.

The height of the barrier is modulated by the body doping concentration. Hence with increasing the body doping level, more carriers flow through the channel and output current will increase.

IV. . Conclusion

The self-consistent solution of the Schrodinger and Poisson equations has been performed to extract I-V characteristics of carbon nanotube FET with a coaxial gat**e** and zigzag nanotube with (16,0) chirality. For this device, the body doping concentration is increased to N_b=1×e^{9}cm^{-3} and results are shown in Fig. 2-7. According to results, with increasing body doping concentration level, the output current, energy profile and electron density of CNTFET will increase and the I_{ON}/I_{OFF} ratio will decrease.

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References

[1] G. E. Moore, “Cramming more components onto integrated circuits. In: Electronics,” *Electronics*, vol. 38, no. 8, p. 114, 1965.

[2] F. Karbassian, M. Moradinasab, and M. Fathipour, “Numerical study of scaling issues of C-CNTFETs,” in *2009 1st Asia Symposium on Quality Electronic Design, ASQED 2009*, 2009.

[3] Itrs, “International Technology Roadmap for Semiconductors, Executive Summary,” *Itrs*, 2011.

[4] M. Haselman and S. Hauck, “The future of integrated circuits: A survey of nanoelectronics,” *Proc. IEEE*, 2010.

[5] J. D. Plummer and P. B. Griffin, “Material and process limits in silicon VLSI technology,” *Proc. IEEE*, 2001.

[6] S. Iijima, “Helical microtubules of graphitic carbon,” *Nature*, 1991.

[7] C. Chen and Y. Zhang, “Review on Optimization Methods of Carbon Nanotube Field-Effect Transistors,” *Open Nanosci. J.*, 2007.

[8] M. Pourfath, H. Kosina, and S. Selberherr, “A fast and stable Poisson-Schrödinger solver for the analysis of carbon nanotube transistors,” *J. Comput. Electron.*, 2006.

[9] M. N. O. Sadiku and M. N. O. Sadiku, “Moment Methods,” in *Numerical Techniques in Electromagnetics with MATLAB®*, 2018.

[10] D. L. John, L. C. Castro, P. J. S. Pereira, and D. L. Pulfrey, “A schr??dinger-poisson solver for modeling carbon nanotube FETs,” in *2004 NSTI Nanotechnology Conference and Trade Show - NSTI Nanotech 2004*, 2004.