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Modeling and Simulation of Carbon Nanotube Field Effect Transistors

A THESIS

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STATEMENT

This thesis is submitted to Ain Shams University in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Electronics and Communications Engineering.

The work included in the thesis was carried out by the author at the Electronics and Communications Department, Faculty of Engineering, Ain Shams University, Cairo, Egypt.

No part of this thesis has been submitted for a degree or a qualification at any other university or institute.

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ABSTRACT

Mostafa Hassan Abbass Fedawy, "Modeling and Simulation of Carbon Nanotube Field Effect Transistors," Doctor of Philosophy Dissertation, Ain Shams University, 2013.

Aggressive scaling of silicon based transistors has led to higher integration density, higher circuits performance, and low power consumption. However, it is expected to reach to its limit by 2020. Carbon Nanotube Field Effect Transistor (CNTFET) is currently considered as a promising nanoelectronic devices because of their small nanometric size and their ability to carry high current. Moreover, it can avoid most of traditional Metal Oxide Semiconductor Field Effect Transistor (MOSFET) limitations.

The present work proposed a simple and accurate numerical model for MOSFET-Like Single-Wall Carbon Nanotube Field Effect Transistors (SW-CNTFET). The tight bending and zone folding methods are used to calculate the subband minima accurately. Unlike the previous numerical models, our proposed model can be used for any Carbon Nanotube (CNT) chirality as long as the CNT is semiconductor. Moreover, it is applicable for both low and high gate voltage application; up to 3 V. In addition, we investigate the influence of temperature on the transfer and output characteristics of the MOSFET-Like SW-CNTFET.

The effect of the number of subbands in the drain current calculation is studied. Our results prove that the higher subbands have a drastically effect on the saturation drain current especially for high gate voltage. However, the sub-threshold region characteristics are depended only on the first subband. Furthermore, we study the onset-voltage, the On-/Off-current ratio, and the sub-threshold swing of the SW-CNTFETs. Results show that, the onset-voltage is decreased linearly with increasing the temperature. Moreover, the rate of change in the onset-voltage with temperature is almost independent on the drain voltage. After that, the dielectric material and the dielectric thickness effects on CNTFET performance are studded.

Any numerical model cannot couple with the circuit simulations. For this reason, we propose a fast and accurate empirical model to calculate the subband minima of the CNTFET's channel. Moreover, we proposed an analytical model for the capacitance of CNTFET. Our proposed model shows a good agreement with the numerical model; where it presents a root mean square error within 3.4 %.

Key Words: CNT transistor model, CNTFET varactors, Subband empirical model, MOSFET-Like CNTFET.

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LIST OF SYMBOLS

a'	Lattice constant
a_1	First basis unit vector of graphene
a_2	Second basis unit vector of graphene
a_{c-c}	Carbon-carbon distance
A_P	Fitting parameter for p^{th} subband
b_1	First reciprocal lattice vector
b_2	Second reciprocal lattice vector
B	Number of basis function in a unit cell
B_P	Fitting parameter for p^{th} subband
C_D	Drain capacitance
C_G	Gate capacitance
C_h	Chiral vector
C_{ox}	Oxide capacitance
C_P	Fitting parameter for p^{th} subband
C_Q	Quantum capacitance
C_s	Source capacitance
d	Nanotube diameter
D(E)	Density of states
$D_1(E)$	Density-of-states filled from the source contact
$D_2(E)$	Density-of-states filled from the drain contact
$D_{NT}(E)$	Density of states of the carbon nanotubes
$D_{spin}(E)$	Density of states per spin
E	Total energy
E_C	Conduction band edge
E_{cp}	Conduction band edge of p^{th} subband
E_f	Fermi level
E_{F1}	Source Fermi energy

E_{F2}	Drain Fermi energy
E_{Fo}	Equilibrium Fermi level
E_g	Bandgap of a single wall nanotube
E_i	Intrinsic Fermi level
E_o	Midband gap energy level
E_V	Valence band edge
$f_o(E)$	Equilibrium Fermi function
$F_D(E)$	Fermi-Dirac distribution at the $E = E_{F2}$
$F_s(E)$	Fermi-Dirac distribution at the $E = E_{F1}$
g_o	Metallic density of states
G	Conductance
G_g	Greatest common divisor of (2m+n) and (2n+m)
h	Planck's constant
ħ	Planck's constant divided by 2π
I_d	Drain current
I_{Dp}	Current from the drain to the channel for p^{th} subband
I_L	Current from the left contact to the channel
I_{OFF}	Off-leakage current
I_{ON}	On-state current
I_R	Current from the right contact to the channel
I_{Sp}	Current from the source to the channel for p^{th} subband
k_x	Wave vector in x-direction
k_y	Wave vector in y-direction
K	Allowed wave vectors along the axial direction for a CNT
K_a	Reciprocal lattice vector along the nanotube axis
K_B	Boltzmann constant
K_c	Reciprocal lattice vector along the circumferential direction.
l	Integer number