AIN SHAMS UNIVERSITY

FACULTY OF ENGINEERING

ENGINEERING PHYSICS AND MATHEMATICS DEPARTMENT

Electro-Thermal Analysis for Carbon Nanotube Transistors

A thesis Submitted in Partial Fulfillment of the Requirements of the

Degree of Master in Engineering Physics

By

Walid Soliman Selmy Mohammed

Supervised by:

Prof. Dr. Salah Gamal

Ain Shams University

Dr. Mohammed Elbanna

Ain Shams University

Cairo, 2013

AIN SHAMS UNIVERSITY

FACULTY OF ENGINEERING

Electro-Thermal Analysis for Carbon Nanotube Transistors

By

WalidSolimanSelmyMohammed

Examiners Committee

Name Signature

Prof: **Lotfy Ibrahim Abo Salem**…………………..

Prof: **Omar Abdel Halim Omar**…………………..

Prof: **Salah El din Hassan Gamal**…………………..

Date:…../……/…………

Summary

In the first part of this work, single-wall carbon nanotubes (SWCNTs) are cylinders formed by a sheet of hexagonally arranged carbon atoms (graphene) wrapped into a nanometer-diameter tube. These molecular wires have attracted considerable scientific and engineering interest due to their outstanding electrical and thermal transport properties for this tube. Depending on their wrapping (chiral) angle, SWCNTs exhibit either semiconducting or metallic behavior. Within integrated circuits, semiconducting SWCNTs can be used for transistor device applications, while metallic SWCNTs have been proposed as advanced interconnects. Compared to typical copper interconnects, SWCNTs can carry up to two orders of magnitude higher current densities (~ 10^9 A/cm^2), The thermal conductivity of nanotubes exceeds that of copper by a factor of 15 and is insensitive to electromigration.

In the second part of this work, we analyze transport in metallic single-wall carbon nanotubes (SWCNTs) interconnect over the bias range up to electrical breakdown in air. To account for Joule self-heating, a temperature-dependent Landauer model for electrical transport is coupled with the heat conduction equation along the nanotube. We examine the phonon scattering mechanisms limiting electron transport, and find the strong temperature dependence of the optical phonon absorption rate to have a remarkable influence on the electrical resistance of micron-length nanotubes. For interconnect applications of metallic SWNTs, significant self-heating may be avoided if power densities are limited below 5 μW/μm.

The thesis contains three chapters, conclusion, references list and is organized as given below.

Chapter 1

This chapter gives a background on the structure of carbon nanotubes and its advantages, the electrical properties of metallic single-wall and multiwall nanotubes. A SWCNT can be metallic and semiconducting, dependent on its chirality.

Chapter 2

In this chapter, the electrical and thermal transport in metallic single wall carbon nanotubes interconnect under a wide range of temperature and bias conditions, and comparison of our analysis with previous work are presented.

Chapter 3

The result of our work after its comparison with previous work is presented. The results of comparison show an error between them especially in the low length and high bias.

Finally, the results and discussion of our work after its comparison with pervious work is presented.

Abstract

A carbon nanotube (CNT) that is one possible material that may replace copper interconnects in the near future. As such, it is necessary to develop a method for analyzing their capabilities. A successful model would have the ability to identify potential shortcomings and advantages of CNTs as compared to current interconnect technology. Interconnect was developed to test CNTs of various lengths under an applied variable voltage.

The electro-thermal effects have an important role in the study of metallic Single-Wall Carbon Nanotubes (SWCNTs) for interconnect applications. Experimental data and careful modeling reveal that self-heating is considerably significant in short nanotubes ($1 < \boldsymbol{L} < 15\boldsymbol{\mu}$m) under high-bias. The low-bias resistance of micron scale SWCNTs is also found to be affected by optical phonon absorption (a scattering mechanism previously neglected) above 250 $\boldsymbol{K}$. In this work, we explore the effect of the thermo-electric current ($\boldsymbol{I_{hc}}$) caused by the temperature difference along the SWCNTs interconnects (thermo-electric properties). The thermo-electric current effect is studied at different lengths of SWCNTs and at different biases. Also the change in length has an important role in the value of the breakdown voltage (the breakdown voltage increased as the length of the carbon nanotube interconnects increased).

Acknowledgment

I would like to thank my Allah who shows me the way and makes me able to finish this work (**Thanks my Allah**).

The help of many people achieved the completeness of this work. First, I would like to thank my supervisor **Prof. Salah H. Gamal** for his help, assistance, and encouragement during the years. No words are sufficient to express my deep gratitude toward my supervisor **Dr. mohammed elbanna** who gives me a lot of time and helpful advices and materials over the years. He was not only my supervisor but also an example I think I will never be in his level.

Many thanks to **Prof. tarik mohammed abdoelkader** for his helpful discussions and tutorials. These discussions push the work forward.

I would like to express my heartfelt thanks to my beloved my father, my mother and my brother for her blessings, my wife for her help and my sons wishes for the successful completion of this work.

Contents

List of Abbreviation

Cu	copper
SWCNT	single wall carbon nanotube
MWCNT	multi wall carbon nanotube
1 D	one dimensional
2 D	two dimensional
GNR	graphene
T	translational vector
OP	optical phonon
AC	acoustic
DOS	density of state
MFP	mean free path

List of Figures

List of Publications

[1] Walid Soliman, Tarek M. Abdolkader, Mohammed M. El-Banna and Salah H. Gamal, "A Novel Electro-Thermal Model for Carbon Nanotube Interconnects", J. Am. Sci. 9(4):511-518, (2013).

List of Symbols

J	current density
a_1 and a_2	unit vectors in real space
a	lattice constant
b_1 and b_2	the unit vectors in reciprocal space
a_{c_c}	carbon-carbon bond length
E	energy dispersion
C_h	chiral vector
Θ	chiral angle
d_t	diameter of carbon nanotube
$N(E_F)$	the density of states per unit length
V_f	Fermi velocity
h	Planck constant
E_g	energy gap
G	thermal conductance
L	channel lengths
Lm	Mean Free Path
V_g	group velocity
k_B	Boltzmann constant
T	the temperature
λ_{eff}	effective electron mean free path
V_f	electron Fermi velocity
λ_{AC}	elastic scattering mean free path
$\lambda_{AC,300}$	AC scattering length at 300 K
N_{OP}	The OP occupation number
I	current
V	voltage
$\lambda_{OP,abs}$	the OP absorption length

$\lambda_{OP},_{300}$	the spontaneous OP emission length at 300 K
$\lambda_{\mathrm{OP},\mathrm{ems}}$	optical phonon emission mean free path
R_C	the electrical contact
e	the electronic charge
g	heat loss coefficient from the tube into the substrate
T_{BD}	breakdown temperature
A	cross-sectional area
b	thickness of the tube
K_{th}	thermal conductivity
P	Joule heating rate per unit length
$T(x)$	temperature profile
T_o	ambient temperature
L_H	characteristic thermal healing length
σ	electrical conductivity
S	thermopower
N	the total number of acoustic modes
ΔT	the temperature difference along the nanotube
α	The differential Seebeck coefficient
π	peltier coefficient
τ	Thomson Coefficient
W_{hc}	The thermo-electric current

List of Tables