MODELING OF GRAPHENE NANORIBBON FIELD EFFECT TRANSISTOR

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Dedicated to Emam Zaman and my beloved family

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ABSTRACT

The scaling of Field Effect Transistor (FET) at nanoscale assures better performance of the device. The phenomenon of downsizing the device dimensions has led to challenges such as short channel effects, leakage current, interconnect difficulties, high power consumption and quantum effects. Therefore, new materials and device structures are needed as alternatives to overcome these challenges. In this research, an analytical model for Trilayer (ABA-stacked) Graphene Nanoribbon carrier statistics based on quantum confinement effect is presented. To this end, density of states, carrier concentration and ballistic conductance of Trilayer Graphene Nanoribbon (TGN) as an FET channel are modeled. Besides that, scaling behaviors of p-n junction, Homo junction, Schottky-barrier diode and Schottky-barrier FET based on the Graphene Nanoribbon application are analytically studied. This is demonstrated in the proposed structure of TGN Schottky-barrier FET that exhibits negligible short channel effects, improved on current, pragmatic threshold voltage, very good subthreshold slope, and fast transient between on-off states to meet the International Technology Roadmap for Semiconductors (ITRS) near-term guidelines. Therefore, the proposed model is suitable for a high speed switching application because the value of subthreshold slope for the proposed transistor is less than the ideal value of 60 mV/decade. A small value of subthreshold slope denotes a small change in the input bias which can modulate the output current and would lead to less power consumption. Finally, an analytical modeling of Graphene-based NO_2 gas sensor is proposed. MATLAB software was used to implement the numerical methods for modeling and data analysis. Observations of the presented models showed acceptable agreement with the published data.

ABSTRAK

Pengskalaan Transistor Kesan Medan (FET) pada tahap nanometer menjamin prestasi yang lebih baik untuk peranti berkenaan. Fenomena pengecilan dimensi peranti membawa beberapa cabaran seperti kesan saluran pendek, arus kebocoran, kesukaran penyambungan, penggunaan kuasa yang tinggi dan kesan kuantum.Oleh itu bahan-bahan baru dan struktur peranti diperlukan sebagai alternatif untuk mengatasi cabaran ini. Dalam penyelidikan ini model analisis statistik pembawa tiga lapisan (susunan ABA) Nanoribbon Grafin berdasarkan kesan berpantang kuantum digunakan. Untuk maksud ini ketumpatan keadaan, kepekatan pembawa dan kealiran balistik Nanoribbon Grafin tiga lapisan (TGN) sebagai saluran FET dimodelkan. Selain itu perilaku berskala simpang p-n, simpang Homo, diod halangan-Schottky dan FET halangan-Schottky berdasarkan applikasi Nanoribbon Grafin dianalisis secara analitikal. Ini menunjukkan bahawa struktur cadangan TGN FET halangan-Schottky mempamerkan kesan saluran pendek yang boleh diabaikan, memperbaik arus voltan ambang pragmatik, sub-ambang cerun yang sangat baik, cepat bertukar antara keadaan hidup-mati untuk memenuhi garis panduan *International Technology Roadmap for Semiconductors* (ITRS) dalam jangka masa terdekat. Dengan itu model yang dicadangkan sesuai untuk aplikasi pensuisan berkelajuan tinggi kerana nilai cerun sub-ambang untuk transistor yang dicadangkan adalah kurang daripada nilai ideal 60 mV/dekad. Satu nilai yang kecil cerun sub-ambang menandakan perubahan kecil pincangan input yang boleh memodulasi output semasa dan mengurangkan penggunaan kuasa. Akhirnya, pemodelan analitikal Grafin berasaskan pengesan gas NO_2 telah dicadangkan. Perisian MATLAB digunakan untuk melaksanakan kaedah berangka untuk pemodelan dan penganalisisan data. Pemerhatian terhadap model yang dibentangkan menunjukkan persamaan yang boleh diterima dengan data yang diterbitkan.

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LIST OF SYMBOLS

a_1,a_2 - Vectors of Lattice

a_{c-c} - Carbon-Carbon (C-C) bond length

C - Chiral vector

$D(E)$ - Density of State

E_c - Conduction band

E_f - Fermi energy level

E_g - Band gap energy

E_v - Valence band

G - Conductance

h - Plank’s Constant

k - Wave Vector

k_B - Boltzmann’s Constant

L - Length of the nanoribbon

m^* - Effective mass

N - Number of dimer lines

N_c - Competition Degree

η_f - Normalized Fermi energy

Q - Charge

t - C-C bonding Energy

T - Temperature

v_F - Fermi velocity

eV - Electron-volt

$f(E)$ - Fermi-Dirac integral

$1D$ - 1-Dimensional

$2D$ - 2-Dimensional

n - Free electrons concentration

p - Free holes concentration
N_A - Impurity (accepter) concentration in p-type silicon
N_B - Impurity concentration in (n or p-type) bulk silicon
N_D - Impurity (donor) concentration in n-type silicon
Lg - Channel length
L_{eff} - Effective channel length
μ_n - Electron mobility in the channel
μ_p - Hole mobility in the channel
μ_{eff} - Effective channel mobility
λ - Channel length modulation factor
ε - Dielectric constant
ε_s - Permittivity of silicon
α - Body factor term
γ - Body-effect coefficient
t_{ox} - Oxide thickness
W - Effective or electrical channel width
W_d - Channel-depletion width
W_j - Junction width
X_j - Junction depth
C_{ox} - Capacitance per unit area
AC - Alternating current
DC - Direct current
V_D - Drain voltage
V_{DD} - Power supply voltage
V_{DS} - Drain to source voltage
V_{Dsat} - Drain saturation voltage
V_G - Gate voltage
V_{GS} - Gate to source voltage
V_{PT} - Punch-through voltage
V_{SB} - Source to bulk voltage
V_T - Threshold Voltage
V_{T0} - Threshold voltage for $V_{SB}=0$

ΔV_{DS} - Change in the drain-source voltage

ΔV_{T} - Change in the threshold voltage

S_T - Subthreshold swing

I_D - Drain current in a MOSFET

I_{DS} - Drain to source current

I_{OFF} - Off-state current or leakage current

I_{ON} - On-state current or drive current

LIST OF ABBREVIATIONS

BGN	-	Bilayer Graphene Nanoribbon
BTE	-	Boltzmann Transport Equation
CAD	-	Computer Aided Design
CLM	-	Channel Length Modulation
CMOS	-	Complementary Metal Oxide Semiconductor
CNT	-	Carbon Nanotube
C-V	-	Capacitance-Voltage Characteristics
DGFET	-	Double-gate MOSFET
DIBL	-	Drain induced barrier lowering
DOS	-	Density Of State
DSOI	-	Drain and Source on Insulator
ECAD	-	Electrical Computer Aided Design
FDI	-	Fermi-Dirac integral
FET	-	Field Effect Transistor
GNR	-	Graphene Nanoribbon
GNRFET	-	Graphene Nanoribbon Field Effect Transistor
GIDL	-	Gate Induced Drain Leakage
HBT	-	Heterojunction Bipolar Transistor
HDD	-	Highly Doped Drain
ITRS	-	International Technology Roadmap for Semiconductors
I-V	-	Current-Voltage Characteristics
LDD	-	Lightly Doped Drain
LOCOS	-	Local Oxidation of Silicon
MOSFETs	-	Metal Oxide Semiconductor Field Effect Transistor
ND	-	Non-degenerate
NMOS	-	n-channel MOSFET

PECVD	-	Plasma Enhanced Chemical Vapor Deposition
PMOS	-	p-channel MOSFET
RIE	-	Reactive Ion Etching
SB	-	Schottky-barrier
SCE	-	Short Channel Effect
S/D	-	Source and Drain
SEM	-	Scanning Electron Microscopy
SGFET	-	Single-gate MOSFET
SOI		Silicon On Insulator
TCAD		Technology Computer Aided Design
TED	-	Transient Enhanced Diffusion
TEM	-	Tunneling Effect Microscopy
TGN	-	Trilayer Graphene Nanoribbon
VLSI	-	Very Large Scale Integrated

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CHAPTER 1

INTRODUCTION

1.1 Background Study

The approaching scaling of Field Effect Transistors (FETs) in nanometer scale assures the smaller dimension, low-power consumption, very large computing power, low energy delay product and high density as well as high speed in processor. The downscaling phenomena of device dimensions lead to some problems such as short-channel effects, gate-leakage current, and so forth. Therefore, novel device structures and materials like graphene, carbon nanotube (CNT), nano scroll, and nano wire are explored for experimentation; more challenges as well as opportunities emerge to expand the vision encountered in the International Technology Roadmap for Semiconductors (ITRS).

According to the Moore's law, the number of transistors per square inch on integrated circuits doubles approximately every two years (Gordon, 1965). It is noteworthy that the capabilities of many digital electronic devices such as processing speed, memory capacity, sensors and even the number and size of pixels in digital cameras are strongly linked to Moore's law. All of these are improving exponentially rates as well, which has dramatically enhanced the impact of digital electronics in nearly every segment of the world economy. In future, nanoelectronic devices will be scaled down to nanoscale size to meet the Moore’s law, and therefore, will operate in the degenerate limit, which makes the degenerate approximation more dominant in the future nanoscale device modeling.

Diamond and graphite are the materials which are extensively investigated in nanoelectronic. Since diamond’s unusual bonding attributes makes it hard to be naturally created, the lately discovered allotropes like fullerenes and nanotubes are taken into consideration closely by scientists researching in the fields of biology, chemistry, physics and material science (Gogotsi *et al.*, 1999; Irifune et *al.*, 2003). All the structural studies on graphite, fullerenes and nanotubes start with graphene. Graphene is the name given to a single layer of carbon atoms in form of honeycomb lattice which is the basic structure of the graphite based materials such as nanotubes and fullerenes contain pentagons (Entani *et al.*, 2010; Zhang *et al.*, 2010b; Castro Neto *et al.*, 2009b).

Due to its unique structure, excellent electronics (McEuen *et al.*, 2002), optical (Misewich *et al.*, 2003; Chen *et al.*, 2005) and physical properties, graphene nanoribbon (GNR) has recently been considered for new device applications in the future. Consequently, prototype structures indicating excellent performance for transistors (Javey *et al.*, 2003), interconnects (Li *et al.*, 2003), electromechanical switches (Jang *et al.*, 2005), infrared emitters and biosensors (Kong *et al.*, 2000) have been demonstrated.

It is reported that neither the velocity of the charge carriers at the upper part of the valence band, nor the velocity at the lower part of the conduction band is reduced, which is a common attribute of most materials. In fact, it stays constant throughout the bands (Geim and Novoselov, 2007). The low scattering rates and the electronic structure of GNR result in an excellent electronic transmission which is adjustable by doping or using electrostatic field. It can serve as interconnects due to its high conductivity. Since it can be gated, it could be used as a channel in novel transistors. Because of the stable and inert properties of GNR, it could be adopted to make big areas that have low defect densities and low electronic scattering rates (Geim and Novoselov, 2007).

A significant contributing reason to GNR’s importance is the specific nature of its charge carriers, which is related to the fact that its charge carriers mimic relativistic particles, and is simply described using the Dirac Equation rather than the

Schrödinger Equation (Wehling *et al.*, 2008; Novoselov *et al.*, 2005). The Schrödinger Equation contributes in giving an illustration of electronic properties of materials in condensed matter physics (Wehling *et al.*, 2008; Novoselov *et al.*, 2005). GNR's high electron propagation is essential in creating high speed and high performance transistors. A GNR Metal Oxide Semiconductor Field Effect Transistor (GNR MOSFET) is an appliance, in which a GNR can be applied as the channel of a FET-like device (Schwierz, 2010). However, for GNR MOSFET's being used in realistic IC applications, material properties such as the energy band gap (EG) should be closely controlled. The method of preparing multilayer GNRFET is both appealing and amazing. Trilayer graphene nanoribbon (TGN) as a multilayer GNR can be piled up independently relying on the horizontal shift between consecutive graphene planes, which results in a variety of electronic properties and band structures.

The outcome of this study suggests that graphene based devices have potential to replace conventional silicon MOSFETs in driving the technology forward. It can also be used to evaluate the potential of GNR in integrated circuits incorporating both analog and digital functions which are recognized to exceed CMOS capabilities in term of scalability, speed and power consumption.

1.2 Problem Statement

The GNR (Monolayer, bilayer and trilayer) can be used as a transistor channel in the future. It has unique electronic characteristics such as symmetrical band structures, ballistic transport, and high current. In fact, the development of GNRFET is possible. The aim of this study is to analytically model the p-n and homo junctions of Monolayer GNR, bilayer graphene nanoribbon (BGN) schottky diode, the carrier concentration, ballistic conductance, and ballistic carrier transport of TGN, TGN schottky-barrier (SB) FET, graphene based NO_2 gas sensor and compared with published data. Despite all the research work, at the present moment, the following characteristics of GNR are not clear:

i. Short channel effect in nanoscale devices

The downsizing of channel length in a planar MOSFET causes short channel effect, leakage current, interconnect difficulties, high power consumption and quantum effect. When the channel length reaches nano meter scale, the conventional device modeling is no longer precise due to some parameters. Therefore, new device structures and materials such as GNRs are discovered as an alternative to overcome the challenges.

ii. P-N and homo junctions of monolayer GNRFET modeling

The p-n junction is an essential building block for electronic components. It is expected that GNR p-n and homo junction properties will be different from the traditional semiconductor p-n junctions. Developing a quantitative understanding of GNR p-n and homo junctions is a significant step towards developing novel devices such as GNR transistors and filters. Monolayer GNR p-n and homo junction has turned out to be of significant attention due to the fact that it presents better performance over conventional semiconductor p-n junction diodes in terms of electrical parameters such as turn-on voltage. In this research, a quantitative study of the near equilibrium I-V characteristics of GNR p-n and homo junctions is presented.

iii. Carrier statistics for TGN in Degenerate and Non-degenerate regimes

In previous models, most of the works are based on the charge or non-equilibrium Green Function calculations and three dimensional (3D) modes for the carrier statistics modeling of nanoscale transistor are explored. However, in this case, a one dimensional (1D) calculation for nanoscale devices will be adopted. Majority of the models calculated carrier concentration of monolayer GNR and BGN using the Maxwell Boltzmann approximation (non-degenerate regime). In this study, 1D visualization of carrier movement based on the band structure of TGN in the presence of a perpendicular electric field is employed. Here, an analytical model of TGN carrier statistics as a fundamental parameter on FET in corporation with a numerical solution is proposed in the degenerate and non-degenerate limits. Furthermore, the efficiency of electron transport is the important quantity that defined as conductance (Datta, 2002). In this research, an introduction of the analytical model and numerical solution of TGN ballistic conductance is also presented. The conductance model can be adopted to derive current-voltage characteristic of TGNFET modeling.

iv. Ballistic carrier transport model for GNRFET structure in Degenerate and Non-degenerate regimes

The carrier transport features for long channel MOSFET model are no longer capable of describing carrier transport perfectly even for sub-100nm MOSFETs. The scattering-dominant transport mainly phonon, coulomb and surface roughness scattering usually occurs in the classical devices. The model is basically obtained from the Boltzmann Transport Equation (BTE) in a classical manner by invoking many simplifying closure approximations. To incorporate the quantum-mechanical effects into classical device simulation, BTE can be coupled to the Schrödinger or Wigner equations. Consequently, it is necessary to take the quantum transport into consideration when describing non-classical current transport models for nanoscale transistors such as GNRFET which operates in the quasi-ballistic transport regime. Therefore, simulation studies that depend on conventional models may incorrectly forecast device performance and physics. It is notable that the ballistic carrier transport model can be utilized to derive current-voltage characteristic of nanoscale GNRFET modeling. In this study, analytical models of monolayer GNR p-n and homo junction diodes, BGN schottky diode and TGN SB FET are developed, which can be adopted for the GNRFET optimization.

v. The monolayer graphene FET based gas sensor modeling

In order to higher accuracy, faster response time and increased sensitivity, sensor technology needs to be developed. Therefore, carbon based materials as a future candidate on sensor technology is promising to response to the huge demand for higher accuracy, faster response time, and increased sensitivity of a sensor. Due to the unique electronic and elasticity properties such as large surface–to–volume ratio, high conductivity, high mobility, strong mechanical, low energy dynamics of electrons with atomic thickness and flexibility, graphene can be utilized in the creation of nanoscale sensors with low power requirements. In this study, the potential of monolayer graphene in generating NO_2 gas sensor is investigated. It is concluded that graphene has great potential as a material for ultra-sensitive gas sensor by optimizing of the device structure.

1.3 Research Objective

The purpose of this study is on the modeling and simulation of GNRs (monolayer, bilayer and trilayer) FET as a 1D device. The objectives of this study are as follow:

i. To analytically model the p-n and homo junctions for monolayer GNR.

ii. To analytically model the carrier statistics and conductance for TGN.

iii. To formulate analytical and semi-empirical equations for ballistic carrier transport in GNRFET.

iv. To analytically model GNRFET based devices.

1.4 Scope of Study

The implementation of this research includes the following:

i. The enhancement of the p-n and homo junction analytical models for monolayer GNR.

ii. The enhancement of the carrier concentration and conductance analytical models for TGN.

iii. The enhancement of the ballistic carrier transport analytical model for GNRFET.

iv. Analytical modeling of GNR based devices such as monolayer graphene FET based gas sensor.

v. Comparison between the proposed models and published data in terms of physical structure and electrical performance of the devices.

1.5 Research Contributions

There are many challenges in the downscaling procedure of conventional MOSFETs, such as short-channel effects, gate-leakage current, and so forth. Therefore, new materials and structure similar to multiple gate MOSFETs, CNTFETs, GNRFETs and molecular based transistors are significant to overcome the downscaling problems. This study mainly focuses on developing a physical model based on GNRFET to find out device behavior, which are very important for optimizing electronic device performance. This research is basically different from other related investigations that are explained as follows:

i. In this study, the quantum confinement effect for modeling transport phenomena in 1D GNRFETs is employed. The energy band structure is the start point of all calculations. The carrier statistics in corporation with a numerical solution for low-dimensional nanostructure is elaborated.

ii. The research develops the analytical models of monolayer GNR p-n and homo junctions, BGN schottky diode and TGN SB FET as a high speed switch.

iii. A general analysis of recent developments in NO_2 gas nanoscale sensor based on monolayer graphene is also presented in this research.

1.6 Thesis Organization

This chapter briefly shows problem statements, objectives and scope of this research. The rest of the thesis is organized to elaborate the key aspects of this research. This section gives an outline of the thesis as follow:

Chapter 2 explains the historical overview of GNR (monolayer GNR, BGN and TGN). It presents a comprehensive overview of energy band structure, which is the key point to understand transport phenomena in quasi 1D material such as GNR. It inclusively reviews the related research in basic geometries of GNR. Furthermore, the historical study of monolayer GNR p-n and homo junctions, BGN schottky diode, TGN SB FET and monolayer graphene FET based gas sensor is briefly presented in this chapter.

Chapter 3 describes the methodology involve in this research. In general, the activities needed for this research is categorized into three phases as described in this chapter. At the next, a general description of the system design and development process is discussed. Finally, the framework of this research is introduced which includes the study in the modeling part and simulation part by MATLAB software. In simulation part parallel to the modeling study, MATLAB software programming will be used intensively.

Chapter 4 outlines the proposed methods for modeling and simulation study of GNR (monolayer GNR, BGN and TGN) based FET models. This chapter proposes analytical modeling of monolayer GNR p-n and homo junction, BGN schottky diode performance. Additionally, quantum confinement effect of TGN carrier concentration, the effect of applied voltage on the TGN carrier effective mass, the conductance of TGN and also analytical modeling of TGN SB FET for high speed switching applications are discussed in this chapter. At the end, the simulated results are shown and discussed.

Chapter 5 presents the monolayer graphene FET based gas sensor application. Analytical modeling of monolayer graphene FET based NO_2 gas sensor is presented in this chapter. The comparison of proposed model with published data is illustrated by diagrams and charts, and good agreement is reported.

Chapter 6 briefly summarizes the thesis with some conclusions. However, the proposed models show a promising improvement in obtained results. Furthermore, the challenging and emerging trends identified fir future research are also suggested in this chapter.

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