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Effect of parametric variation on the performance of single wall carbon nanotube based field effect transistor

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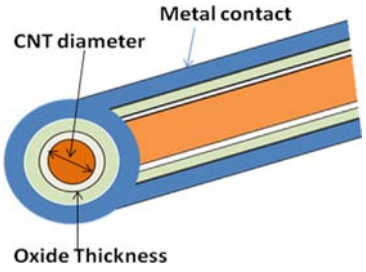
HIGHLIGHTS

- The effects of dielectric constant and gate insulator thickness on the performance of SWCNT-FETs were studied.
- SWCNT-FET has a considerable advantage over conventional MOSFETs.
- As the I_{ON} increases on scaling down the gate oxide thickness, the level of I_{OFF} is not affected.
- The thickness of thin oxide layer causes drastic increase in gate leakage current.
- Thinner gate oxide and high-k dielectric material have improved the performance of CNT-FETs.

GRAPHICAL ABSTRACT

The effects of dielectric constant and gate insulator thickness on the performance of CNT-FETs have been analyzed using a mathematical model based on FETToy simulator and results showed that thinner gate oxide and larger CNT improved the performance of CNT-FETs. Therefore, the performance of the simulated CNFETs using this model has clear lead over those of conventional MOSFETs. The geometry of the FETToy model is shown in figure.



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ABSTRACT

The effects of dielectric constant and gate insulator thickness on the performance of single wall carbon nanotube field effect transistors (CNTFETs) have been analyzed using a mathematical model based on FETToy simulator. Both the parameters are found to have significant effect on the device performance, particularly the on-current; while the on-current (I_{ON}) increases on scaling down the gate oxide thickness, the level of leakage current (I_{OFF}) is not considerably affected. This is an advantage of CNTFET over conventional MOSFETs where the thickness of thin oxide layer causes drastic increase in gate leakage current. Our analysis results show that thinner gate oxide and larger CNT improve the performance of CNTFETs. Therefore, the performance of our simulated CNTFETs using this model has clear lead over those of conventional MOSFETs.

1. Introduction

Modeling is the process of producing a model which represents the construction and working of some system of interest. It is similar to but simpler than the system it represents. The operation of any prepared model of a system is done by simulations to evaluate the performance of the system under different configurations of interest and over long periods of real time. One purpose of the modeling and simulation is to facilitate the analyst to predict the effect of changes in the system and its subsystem.

Experimentally, vertically aligned freestanding SWCNTs have been successfully grown at low temperatures which are useful for growth on temperature sensitive substrates and for selective

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growth. In the growth processes there are several parameters which require hundreds of processes to optimize the growth of SWCNTs with the highest order of purity and control to synthesize repetitive SWCNTs on desired substrates, preferably silicon, at desired location and orientations. However it might not be feasible to experiment a dozen or a hundred processes to make SWCNTs suitable for various applications especially for semiconducting applications. In this connection, a theoretical/computational model needs to be developed so that theoretical results can be simulated experimentally and best optimization for the synthesis of SWCNTs can be achieved for a choice of applications [1].

From the theoretical point of view, various researchers have already described a wide-variety of theoretical/computational studies to explain the atomistic information of the initial stage of the growth which includes *ab-initio* molecular dynamics (MD) [2–11], classical potential based molecular dynamics [12–18], and classical thermodynamics based growth parameters [19–23]. Nucleation pathway for SWCNTs on a metal surface using a series of total energy calculations based on density functional theory (DFT) was verified by Fan et al. [10]. Ding et al. showed a nucleation development indicating that temperature gradient in the metal particle might be unnecessary as a driving force for nucleation of the SWCNT [12]. Raty et al. illustrated the first stages of the nucleation of a fullerene cap on a metal particle by *ab-initio* MD [9]. Amara et al. [23] focused on the carbon chemical potential during SWCNT formation using tight-binding methods coupled to a grand canonical Monte Carlo (MC) simulation and showed that solubility of carbon in the outermost nickel layer is dominant in controlling the nucleation of SWNTs. All these studies are based on certain models to make SWCNTs better for various applications. Particularly, SWCNTs have grown up as the most likely candidates for miniaturizing electronics beyond current technology. They reveal exceptional electrical and mechanical properties. The most fundamental application of SWCNTs is in field effect transistors (FETs); n-type carbon nanotube field effect transistors and p-type carbon nanotube field effect transistors have been made which show behavior similar to MOSFETs [24].

In this study the model used for the FETToy software is very useful, assuming ballistic transport which produces near-ideal results. These results are based on a limited set of parameters, which controls the software's usefulness for predicting the exact characteristics of a fabricated device. Starting with the dimensions of a fabricated device, it can be useful in analyzing the effects of parameter variation on CNTFET performance. These variations can then be used as a guide for further development and to point toward areas where improvements will yield the best results, which can save fabrication cycles and speed up CNTFET development.

The theoretical basis for CNT-FETToy is a model by Natori for ballistic FETs [25] which has been expanded upon by Rahman [26]. Numerical simulations such as the ballistic Boltzmann equation and the non-equilibrium Green's function (NEGF) provide detailed information about nanoscale devices, but are very complex. The goal of the expanded model is to develop a simple analytical model for determining the current–voltage characteristics that can produce accurate results without needing to specifically address all of the complex phenomena that take place within the device.

The work presented in this article will focus on modeling and simulation of SWCNT based field effect transistors (CNTFETs) by changing the device's structure and includes various effects on device performance of variations in the transistor's structural parameters such as CNT diameter, gate dielectric thickness, and gate dielectric constant. Using these parameters, current–voltage (*I–V*) characteristics have been simulated under different parametric variations.

2. Model

The simulations in this work are conducted by FETToy 2.0 software which is a product of nanoHUB, an internet-based website funded by the National Science Foundation's (NSF) Network for Computational Nanotechnology (NCN) and Purdue University [27]. It is a numerical simulator which uses a set of Matlab scripts to calculate ballistic *I–V* characteristics for conventional single and double gate geometry MOSFETs, nanowire MOSFETs, and carbon nanotube MOSFETs.

FETToy assumes an optimal CNTFET geometry comprising a single, semiconducting carbon nanotube channel, completely surrounded by an oxide and gate structure, with perfectly contacted ends (Fig. 1). It requires a relatively small number of parameters, divided into three categories.

The model for ballistic CNTFET consists of three capacitors, which represents three transistor terminals on potentials at the top of barrier. As shown in Fig. 2, the shaded region indicates mobile charge at the top of the barrier. The mobile charge is determined by the local density of states at the top of the barrier, location of source and drain levels, E_{F1} and E_{F2}, and self-consistent potential at the top of the barrier.

It is common to think of MOSFETs as operating by modulating the charge in the channel, but this FETToy model focuses on the height of the energy barrier in the channel. The two concepts are linked in that the charge in the channel is controlled by the height of the barrier, but basing the model on the height of the barrier allows a more concise analytical model. The circuit diagram in Fig. 2 shows the simple model that represents the potential at the top of the barrier when taking into account the effect of the three terminals (source, drain, and gate). Calculating the potential at the top of the barrier starts with the terminal biases at zero. This will give the equilibrium electron density at the top of the barrier as

$$N_0 = \int_{-\infty}^{+\infty} D(E) f(E - E_f) dE \tag{1}$$

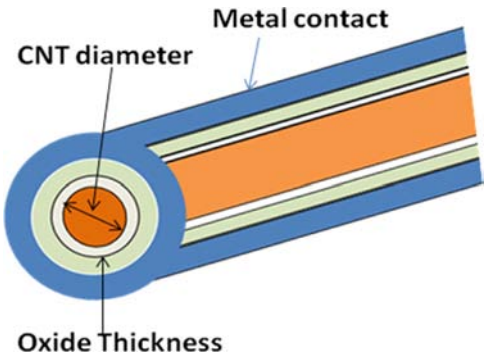

Fig. 1. The optimal geometry assumed in the FETToy model: (i) device, (ii) models and (iii) environment.

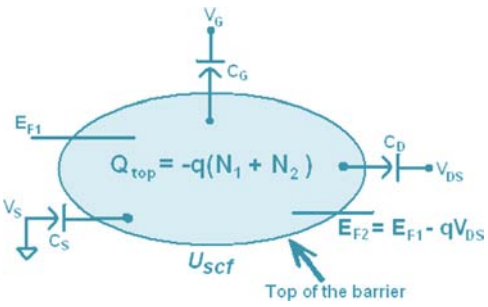

Fig. 2. 2D circuit model for a ballistic transistor.