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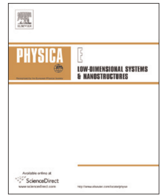

A novel graphene nanoribbon field effect transistor with two different gate insulators

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HIGHLIGHTS

- A novel structure with two different gate insulators for GNRFET (TDI-GNRFET) is proposed.
- Mode-space Non-Equilibrium Green's Function (NEGF) formalism in the ballistic regime is used.
- TDI-GNRFET has lower leakage current and higher I_{on}/I_{off} ratio in comparison with low-K GNRFET.
- TDI-GNRFET has smaller capacitances and lower intrinsic delay in comparison with high-K GNRFET.
- The proposed TDI-GNRFET has good Drain Induced Barrier Lowering (DIBL) and subthershold swing.

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ABSTRACT

In this paper, a novel structure for a dual-gated graphene nanoribbon field-effect transistor (GNRFET) is offered, which combines the advantages of high and low dielectric constants. In the proposed Two Different Insulators GNRFET (TDI-GNRFET), the gate dielectric at the drain side is a material with low dielectric constant to form smaller capacitances, while in the source side, there is a material with high dielectric constant to improve On-current and reduce the leakage current. Simulations are performed based on self-consistent solutions of the Poisson equation coupled with Non-Equilibrium Green's Function (NEGF) formalism in the ballistic regime. We assume a tight-binding Hamiltonian in the mode space representation. The results demonstrate that TDI-GNRFET has lower Off-current, higher On-current and higher transconductance in comparison with conventional low-K GNRFET. Furthermore, using a top-of-the-barrier two-dimensional circuit model, some important circuit parameters are studied. It is found that TDI-GNRFET has smaller capacitances, lower intrinsic delay time and shorter power delay product (PDP) in comparison with high-K GNRFET. Moreover, mobile charge and average velocity are improved in comparison with low dielectric constant GNRFET. The results show that the TDI-GNRFET can provide Drain Induced Barrier Lowering (DIBL) and Subthreshold Swing near their theoretical limits.

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1. Introduction

Conventional Si-CMOS devices have been utilized in the semiconductor industry for decades. Nowadays, it is really difficult to keep up with Moore's Law because of several challenges and limitations [1].

Graphene is a honeycomb two dimensional carbon material. It has absorbed most interest in theoretical and experimental scopes due to its novel electronic characteristics, such as high mobility and good compatibility with common planar semiconductor technology. Graphene is a zero gap material; nevertheless, when patterned into nanoscale ribbons, a bandgap opens due to the lateral quantum confinement. The narrow stripes of graphene with width less than 100 nm, known as graphene nanoribbons (GNRs), are quasi-one-dimensional materials exhibiting finite energy gaps [2,3]. GNRs can be either metallic or semiconductor depending on the crystallographic direction of the ribbon axis. The oscillatory behavior of band gap is predicted for semiconducting narrow armchair ribbons as a function of their width [4].

Graphene can be an evolutionary replacement to conventional CMOS where it replaces Si as the channel material. Therefore, Graphene nanoribbons are being as a promising candidate for the next generation of transistors, specifically as the channel for transistors, because of their excellent transport properties [5,6]. Transistors made of GNRs are called Graphene-Nano-Ribbon Field

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Effect Transistors (GNRFETs), which have been explored in recent studies as potential alternatives to CMOS devices [1].

The gate-leakage current is an important device parameter that takes a major hit due to continued scaling. Device scaling requires gate oxide thickness (t_{ox}) to be scaled for maintaining high On-current (I_{on}) and reducing short channel effects. The gate dielectric leakage current increases with reducing the oxide thickness and becomes the most important contributors of the Off-current (I_{off}). This leakage current over many millions of transistors on a chip results in a large power dissipation which can burn out the chip [7,8].

In order to reduce transistor leakage current, researchers have looked for years at the alternative gate dielectric materials. They found that the gate dielectric material with high dielectric constant will increase gate capacitance without the existence of leakage current. While using a material with a lower dielectric constant as gate dielectric material will reduce parasitic capacitances [9,10].

In this paper, a new GNRFET design based on two different dielectric materials is offered. In the proposed device that is called Two Different Insulators GNRFET (TDI-GNRFET), the gate insulator is made of both high and low dielectric constant materials. In order to simulate the device characteristics; we solve the Schrödinger equation coupled with the Poisson equation in the ballistic regime, using the NEGF in a mode space representation. We employ the tight-binding method in our study [6]. The results are investigated and compared with the conventional structures of GNRFET. Furthermore, we have used a two-dimensional circuit model for analyzing the GNRFETs. It is an endeavor to extract important characteristics of the GNRFETs such as gate, source, drain and quantum capacitances, intrinsic delay time, power-delay product, mobile charge, average velocity, DIBL and subthreshold swing.

This paper is organized as follows: Section 2 presents device geometry which contains conventional GNRFET and the proposed TDI-GNRFET structure. Section 3 represents the calculation method for simulation of the aforementioned GNRFETs. A two-dimensional modeling method is introduced in detail in Section 4, and the modeling results are shown in this part as well. Finally, Section 5 concludes this paper.

2. Device geometry

Fig. 1 shows a schematic representation of the dual-gated GNRFET in conventional structure. The channel material is

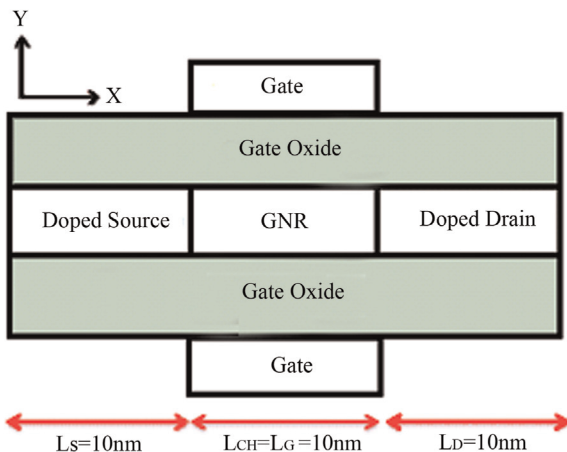

Fig. 1. Schematic of a dual gated GNRFET with a conventional structure.

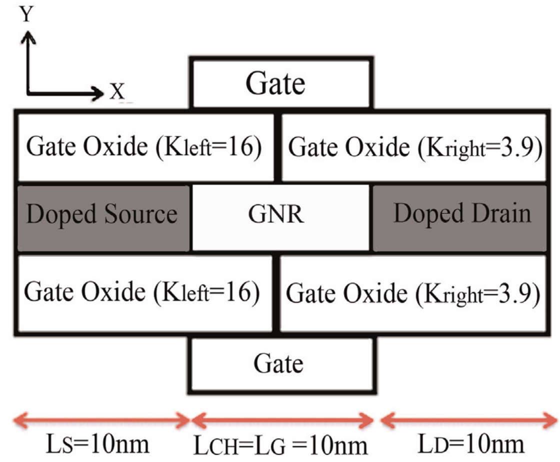

Fig. 2. The proposed structure for TDI-GNRFET.

assumed to be a single-layer armchair graphene nanoribbon (A-GNR) with an index of $n = 12$, sandwiched between two layers of gate oxides. The index n, denotes the number of dimmer carbon atom lines transverse to transport direction. The width and length of this GNR channel are assumed to be $W = 1.35$ nm and $L = 10$ nm, respectively. The thickness of each insulating layer is chosen to be $t_{ox} = 1.5$ nm. The channel is taken to be intrinsic; the source and drain regions are assumed to be heavily doped GNR with doping concentration value of 5×10^{-3} dopants per carbon atom.

As earlier mentioned, we present a new structure of dual-gated GNRFET with two different gate insulators. Fig. 2 shows the schematic of the TDI-GNRFET. Our proposed structure has two different gate insulators. It benefits the advantages of materials with high and low dielectric constants. Keeping this in mind, the gate length of the transistor shown in Fig. 1 is divided into two equal sections, which can be seen in Fig. 2. In order to decrease the capacitances, the gate dielectric at the drain side (right side) is selected as a material with low dielectric constant ($K_{right} = 3.9$). Contrarily, the gate dielectric at the source side (left side) is chosen as a material with high dielectric constant ($K_{left} = 16$) to improve On-current and reduce leakage current.

3. Implementation method

The Non-Equilibrium Green's Function (NEGF) formalism is used to solve the Schrödinger equation in the ballistic regime, together with the self-consistent solution of the two-dimensional Poisson equation. Device Hamiltonian for the GNR is determined by the tight-binding method. To decrease the computational cost of the simulations, the mode space approach is used. This method enables us to decouple the two-dimensional problem into one-dimensional decoupled lattices, which reduce the size of the problem in comparison with the real-space mode [6,11].

Description of the NEGF method has been explained in Refs. [12,13]. The basis of this method was on obtaining the retarded Green's function of the device as computed by the following equation:

$$G(E) = \left[(E + i0^{+})I - H - U - \sum_{S} - \sum_{D}\right]^{-1} \quad (1)$$

where $\sum_S$, $\sum_D$, H, E and I are self-energy of the source contact, self-energy of the drain contact, Hamiltonian matrix of the device, energy value and identity matrix, respectively. U is the self-consistent potential matrix that is determined by the solution of a two dimensional (2-D) Poisson equation. The local density of states

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