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Double gate graphene nanoribbon field effect transistor with single halo pocket in channel region

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ABSTRACT

A new structure for graphene nanoribbon field-effect transistors (GNRFETs) is proposed and investigated using quantum simulation with a nonequilibrium Green's function (NEGF) method. Tunneling leakage current and ambipolar conduction are known effects for MOSFET-like GNRFETs. To minimize these issues a novel structure with a simple change of the GNRFETs by using single halo pocket in the intrinsic channel region, “Single Halo GNRFET (SH-GNRFET)”, is proposed. An appropriate halo pocket at source side of channel is used to modify potential distribution of the gate region and weaken band to band tunneling (BTBT). In devices with materials like Si in channel region, doping type of halo and source/drain regions are different. But, here, due to the smaller bandgap of graphene, the mentioned doping types should be the same to reduce BTBT. Simulations have shown that in comparison with conventional GNRFET (C-GNRFET), an SH-GNRFET with appropriately halo doping results in a larger ON current (Ion), smaller OFF current (Ioff), a larger ON–OFF current ratio (Ion/Ioff), superior ambipolar characteristics, a reduced power–delay product and lower delay time.

1. Introduction

Graphene, a 2D atomically thin film of carbon, has attracted much concern because of its exceptionally high mobility of carriers [1] and due to its ultra-thin body structure which is a valuable property for overcoming short channel effects in scaled-down devices [2]. These attractive properties introduces GNRs as one of candidates for using as channel in field effect transistors. Ambipolar conduction of electron and holes in GNR beside the lack of bandgap are major issues which cause to some problems for application of GNR in complementary metal oxide semiconductor (CMOS) devices [3,4]. Large off state current is direct consequence of using digital devices with small bandgap GNR. The bandgap of GNR depends on its width and edge configuration. By changing GNR width and edge configuration, its bandgap is tunable. Thus it is possible to develop a GNR with determined bandgap for digital applications. Some of famous methods are lithography and bottom–up fabrication to develop GNRs with narrow width [4].

As mentioned above, by changing the GNR width it is possible to have devices with different electronic characteristics. In recent years, researchers have proposed new structures in order to change device characteristics and enhance the GNRFET performance. These new structures include some variations in conventional one to remove GNRFET deficiencies and enhance the device performance [5–13]. These novel structures and previous methods for manipulation of GNR electronic structure,

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more pushing GNR forward to be as a predictable applicant for applying on future nanoelectronic devices. Improving the device performance by proposing new structures for FETs has been noticed in literature. Researchers enhanced main characteristics of devices by applying some modifications on conventional structures. One of these modifications is using a pocket of doped region at source side of channel which called single halo structure [14–19]. In this simple and effective idea, the doping type of halo region is different from that of source and drain regions. In past years, the local high doping concentration in the channel near source/drain junctions has been implemented via lateral channel engineering, for example in Refs. [14,15,19]. Single halo MOSFET structures have been introduced for bulk [16] as well as for SOI MOSFETs [17] and SH-CNTFETs [18] to adjust the threshold voltage and enhance the device performance.

In the presence of halo implantation for Si transistors, some of main characteristics such as breakdown voltage, kink effect, flatness of saturation current, drain induced barrier lowering (DIBL), drive current, leakage current, different short channel parameters and so on have been evaluated and compared with conventional MOSFETs. Results show considerable improvements in these parameters and more demonstrate the suitability of single halo structure for CMOS digital circuits [19]. These improvements have been seen for CNTFETs, too [18]. Beside all of these advantages, there is a significant disadvantage for SH structure where high saturation current is a key factor. Threshold voltage growth is a direct result of halo doping implantation where saturation current decreases. It is remarkable that leakage current suppression is more evident than saturation current reduction so, current ratio enhances in SH structures. The effectiveness of SH structure in different technologies has been proved. However, no such attempt (application of single halo) has been reported on GNRFETs. So, in this paper application of single halo on channel region of GNRFETs is proposed and investigated. The features of SH-GNRFET are explored using quantum simulation study and compared with conventional structure. Saturation and leakage current, current ratio, switching behavior in terms of delay time and power-delay product are investigated and compared at both structures. Different channel lengths have been investigated for more representing the dominance of proposed structure. As mentioned before, application of SH on other technologies reduces saturation current. It is shown that the proposed structure doesn't moderate saturation current which is a substantial advantage for SH-GNRFET.

After introduction, in Section 2 some details about simulation approach are discussed and the conventional and proposed structures are introduced with more details. In this paper, to assess the essential physics of SH-GNRFET and C-GNRFET at different biases and various physical parameters, a full quantum mechanical simulation is used. The results of comparing both devices are mentioned and analyzed in Section 3. The final results of this paper are summarized in Section 4 as conclusion.

2. SH-GNRFET physical structure and its simulation process

Doping distribution along the GNR for source, gate, and drain regions and schematic cross-sectional views are illustrated in Fig. 1 for conventional and SH-GNRFET structures. Each structure includes two gates with two oxides as gate insulator. Gate metals are the same and situated at up and down part of devices. An $N = 13$ A-GNR is used in which N represents the number of dimmer carbon atoms. GNR is in the middle of structures and the devices have same symmetry. The difference between structures is only in halo pocket of doping for SH-GNRFET located at source side of channel. As can be seen from figure, total device length is identical at both structures and there is no space penalty resulted from existence of supplementary halo region. Channel region in conventional structure is totally intrinsic while in SH structure includes an intrinsic and an n-doped halo region. Source and drain regions are doped by n-type doping at both structures. Table 1 summarizes the devices physical parameters. Halo length is 5 nm and its doping density is half of source (drain) doping density. Any change in halo doping, halo length and other physical parameters is stated clearly along the paper.

Poisson and Schrodinger equations should be solved self consistently to simulate the device behavior. In simulations, the device should be discretized to be evaluated point by point. The mentioned equations are assessed in these discretized cells. The finite difference method is used in simulations. By a primary gest for charge distribution, Poisson equation is evaluated to obtain the electrostatic potential spreading all over the device. This voltage distribution is inserted in Schrodinger equation to get fresh charge distribution. Again, this charge distribution is used by Poisson equation to estimate new electrostatic potential. This loop is cut when self-consistency is achieved. Quantum simulation study is based on the nonequilibrium Green's function (NEGF) formalism. Mode space is chosen as a fast space to solve equations. The ballistic transport is assumed in all simulations. In the following some details about simulation approach are described meanwhile more details can be explored in Refs. [20–23].

Hamiltonian matrix should be developed to calculate charge density. In this paper, this matrix is developed with more accuracy by taking some effects into account. One of these effects is third nearest neighbor effect (3NN). Taking the more neighboring atoms into account in simulation, the more accurate Hamiltonian matrix. First and third NN are considered while 2NN is neglected because it only moves the dispersion explanation in energy direction. The hopping integral for 3NN interactions is 0.2ev [22,24,25]. Another effect which is considered to increase the accuracy of Hamiltonian matrix is the effect of edge carbon atoms. Inside the GNR, each carbon atom is connected to three adjacent atom and interatomic distance is 1.42A. Carbon atoms at the edge of GNR are connected to just two carbon atoms and their interatomic distance is smaller, i.e. 1.36A [24]. This effect is included in simulation by considering a change in hoping parameter as will be described later.

Potential distribution of GNRFET is the output of Poisson equation (equation (1)). Using finite difference technique, the device is discretized and the equation is evaluated by gate, drain, and source voltages as boundary voltages. Second derivation of electrostatic potential (U) depends on the dielectric constant (ε), and the net charge density distribution (ρ) counting the doping density.