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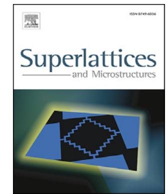

Asymmetric bilayer graphene nanoribbon MOSFETs for analog and digital electronics

A. Dinarvand [a, *], V. Ahmadi [b], Gh. Darvish [a]

[a] Department of Electrical Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran
[b] Faculty of Electrical and Computer Engineering, Tarbiat Modares University, Tehran, Iran

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ABSTRACT

In this paper, a new structure was proposed for bilayer graphene nanoribbon field-effect transistor (BGNFET) mainly to enhance the electrical characteristics in analog and digital applications. The proposed device uses two metallic gates on the top and bottom of a bilayer graphene nanoribbon, which is surrounded by SiO_2 and connected to heavily doped source/drain contacts. Electrical properties of the proposed device were explored using fully self-consistent solution of Poisson and Schrödinger equations based on the nonequilibrium Green's function (NEGF) formalism. Significant improvements in the electrical behavior was seen in the simulation results for gates asymmetrically biased. The comparison with graphene nanoribbon FET showed that the proposed structure benefited from higher intrinsic voltage gain and cut-off frequency and improved switching characteristics such as delay and I_{on}/I_{off} ratio.

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1. Introduction

Graphene and its bilayers have unique electronic properties, which make them interesting as the channels of field-effect transistors (FETs) [1,2], for instance, reduced backscattering of electrons and long coherence lengths (~400 nm) suggest that ballistic transistors can be realized by these materials [3]. International technology roadmap for semiconductors (ITRS), considers graphene to be among the candidate materials for post-silicon electronics [4].

However, when using graphene as the channel of transistors, the interband tunneling due to the gapless energy spectrum leads to a high off-current, making it not appropriate for digital applications [5–7]. A mechanism for opening up an energy gap in graphene is cutting it into graphene nanoribbon (GNR) [2,8]. The band gap and the electronic properties of the GNRs are strongly dependent on the edge geometry of the ribbon [2,9]. Unfortunately, inevitable edge defects due to the low accuracy of lithographic techniques change the energy gap of GNRs, so the band gap creation by patterning graphene to strips is still unreliable [10]. An alternative policy to establish an energy band gap is to stack two GNRs, forming bilayer graphene nanoribbon (BGN) [11,12]. Compared to GNRs, energy gap in BGNs is less sensitive to edge disorders, therefore these materials do not need to highly precise lithography [13]. One of the most remarkable features of bilayer graphene is the ability to open an energy gap and control its size by an electric field applied perpendicularly to it [13]. This external electric field originated from potential difference between the gates, breaks the inversion symmetry between two carbon layers and changes its

* Corresponding author.
E-mail address: alidinarvand1974@gmail.com (A. Dinarvand).

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bandstructure [14–21]. Based on this modification, its behavior changes from metallic to semiconductor depending on the electric field magnitude. It indicates that BGN-based switchable devices can be realized, such as FETs. Furthermore, this material has low sensitivity to external perturbations [8], and suppresses electrical noise, so BGN-based devices have improved signal-to-noise ratio [13]. In recent years, numerous papers have studied the different types of graphene transistors, such as graphene [21], bilayer graphene [22–24], carbon nanotube [25] and graphene nanoribbon FETs [26], however there has not been a comprehensive study about bilayer graphene nanoribbon field-effect transistors (BGNFETs).

In this paper, we provide an extensive theoretical investigation of bilayer graphene nanoribbon FET for radiofrequency and digital applications. First, we obtain the bandstructure of BGN with armchair-edge, using a precise tight-binding (TB) model, which employs a complete set of hopping energy parameters. The effects of each of these interaction parameters on the bandstructure are investigated, individually. According to this precise TB model, we will then calculate the *I-V* characteristics of the proposed BGNFET with heavily doped source/drain contacts, using fully self-consistent solution of Poisson and Schrödinger equations based on the nonequilibrium Green's function (NEGF) formalism. We show that using bilayer graphene nanoribbon as FET channel material can provide better performance in terms of intrinsic voltage gain, cut-off frequency, switching capabilities such as delay and I_{on}/I_{off} ratio, with respect to monolayer-graphene FETs. In order to investigate the radiofrequency characteristics of our FET, we will use small-signal equivalent circuit.

The model for electronic bandstructure of BGNs and transport of carriers in BGNFETs are described in Section 2, Simulation results are presented and discussed in Section 3, and conclusion is presented in Section 4.

2. Theory

Throughout this work, we consider armchair-edge bilayer graphene nanoribbons (A-BGNs) stacked in the Bernal form, in which the edge atoms are passivated by hydrogen atoms. Since the atomistic bandstructure of BGN channels has a crucial role in determining device performances of BGNFETs [27], we compute the electronic bandstructure of it using a TB approach with a p_z orbital basis. One p_z orbital per atom is enough for atomistic physical description since *s*, p_x and p_y are far from the Fermi level and do not play an important role for electron transport [28]. A BGN consists of two GNR layers arranged in the orientation shown in Fig. 1(a). The intralayer and interlayer hopping energies are represented by arrows in Fig. 1(a), representatively.

The intralayer parameters t_1, t_2, t_3 and t_{edge} represent first nearest neighbor (1NN), second nearest neighbor (2NN), third nearest neighbor (3NN) and edge hopping energies, respectively. In our study, we use the values suggested by Kundu [29] for these parameters, as presented in Table 1 [30].

In this Table, E_{sp} is the on-site energy and s_1, s_2 and s_3 are the orbital overlap terms, which are involved in our model and their effects on the bandstructure are studied. The c–c bonds at the edges, which are also bonded to hydrogen atoms to terminate dangling bonds, are about 3.5% shorter than other bonds inside the ribbon. We use a coupling parameter of $t_{edge} = 1.12t_1$ for the c–c bonds on the edge of the ribbon [28]. The other effect of the existence of hydrogen atoms at the strip edge is altering the on-site matrix elements, which these small changes are neglected as these perturbations rigidly shift the dispersion relations [31].

Several forms of the Hamiltonian for BGNs are used in the literature depending on the approximations used. The original consideration was given by Slonczewski-Weiss-McClure, which included all three interlayer coupling terms [32]. The interlayer hopping energies $\gamma_1 = 0.12t_1$, $\gamma_2 = 0.1t_1$ and $\gamma_3 = 0.04t_1$, depicted in Fig. 1(a), are coupling terms between B1–A2, A1–B2 and A1–A2 (or B1–B2), respectively [33]. The width of the ribbon is $W = \sqrt{3}a\ (N-1)/2$ in which $a = 0.142$ nm is c–c distance and *N* is the number of dimmer lines for armchair ribbon. In BGNs with restricted width, the translational symmetry only occurs in *x* direction, as shown in Fig. 1(a). As a result, a unit cell covering the entire width of the strip is chosen for TB bandstructure calculations. The arrangement and ordering number of atoms in a unit cell of an $N = 5$ BGN, are shown in Fig. 1(b). The distance between two neighboring unit cell is $d = 3a$, as displayed in Fig. 1(a). The interlayer distance is $l = 0.335$ nm [28].

The Hamiltonian describing the spectrum of π electrons in BGN reads

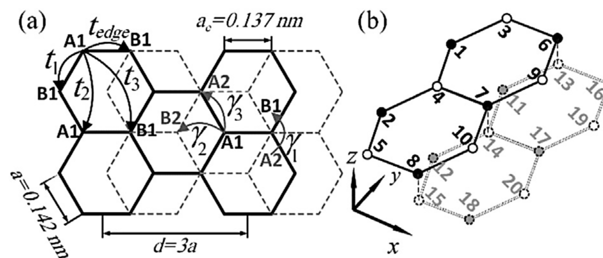

Fig. 1. (a) The top view of the atomic structure of an $N = 5$ BGN with Bernal stacking. Top layer (layer 1) and bottom layer (layer 2) are depicted by solid and dotted lines, respectively. The hopping energies are shown by arrows. (b) The atomic structure of a unit cell of an $N = 5$ BGN. Transport direction is denoted by *x*.

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