Journal of Magnetism and Magnetic Materials 357 (2014) 29–34

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Edge proximity-induced magnetoresistance and spin polarization in ferromagnetic gated bilayer graphene nanoribbon

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ARTICLE INFO

Article history:
Received 5 November 2013
Received in revised form
9 January 2014
Available online 21 January 2014

Keywords:
Spin polarization
Magnetoresistance
Ferromagnetic bilayer graphene
Perpendicular applied gate voltage

ABSTRACT

Coherent spin-dependent transport through a junction containing normal/ferromagnetic/normal bilayer graphene nanoribbon with zigzag edges is investigated by using Landauer formalism. In a more realistic set-up, the exchange field is induced by two ferromagnetic insulator strips deposited on the ribbon edges while a perpendicular electric field is applied by the top gated electrodes. Our results show that, for antiparallel configuration, a band gap is opened giving rise to a semiconducting behavior, while for parallel configuration, the band structure has no band gap. As a result, a giant magnetoresistance is achievable by changing the alignment of induced magnetization. Application of a perpendicular electric field on the parallel configuration results in a spin field-effect transistor where a fully spin polarization occurs around the Dirac point. To compare our results with the one for monolayer graphene, we demonstrate that the reflection symmetry and so the parity conservation fail in bilayer graphene nanoribbons with the zigzag edges.

1. Introduction

The recent successful fabrication of monolayer graphene [1] has been attracted great attention because it prepares appropriate building block for future nanoelectronics and spintronics. The Dirac Hamiltonian at low energy limit of graphene spectrum results in many peculiar properties, for instance, the half integer quantum Hall effect [2], minimum conductivity [3], the absence of back scattering [3,4], Klein tunneling [5]. Furthermore, graphene has excellent transport properties such as long spin relaxation which makes it an excellent candidate for spintronic devices. Because of weak spin orbit coupling, spin relaxation length of graphene can reach about 1 μm in dirty samples and room temperature [6]. Clean samples have longer spin coherency length. Carriers in graphene are not spin-polarized because graphene has no intrinsically ferromagnetism (FM) properties. However, FM can be induced extrinsically in graphene by doping defects [7], Coulomb interactions [8] or by applying an external electric field in the transverse direction in nanoribbons [9]. One of the proposals [10,11] is the proximity effect of a FM insulator deposited on graphene sheet. Because of strong proximity, the wave functions of the localized magnetic states overlap with carriers in graphene sheet giving rise to an induced exchange field in graphene. This induced exchange field which is tunable by application of an in-plane external electric field [12] induces a spin-polarized current in graphene. Using a ferromagnetic gate dielectric which is deposited on graphene layer as the channel, a spin field effect transistor has been proposed when spin manipulation is achievable by applying external perpendicular electric field [13]. External electric field can modify the exchange interaction.

The possibility of controlling spin conductance in monolayer graphene has also been recently studied [14]. It was shown that because of induced exchange field and also due to the chiral resonant tunneling bound states inside the barrier, spin splitting of current emerges and has an oscillatory behavior in respect to the gate voltage and chemical potential. On the other hand, transport gap induced by the parity selection rule governing in the electronic bands of spectrum of zigzag graphene nanoribbons leads to large spin polarization and giant magnetoresistance [15]. Presence of the reflection symmetry in the incoming and outgoing wave functions of zigzag monolayer graphene nanoribbons leads to the parity selection rule which regulates the current flow [16]. We will show in this paper that there is no such symmetry and selection rule in bilayer graphene. Experimentally, possibility of fabrication graphene nanoribbons with ultra narrow widths and atomically smooth edges possibly well-defined zigzag or armchair-edge structures has been recently reported [17]. In zigzag graphene nanoribbons, spin current has also been predicted in the presence of large electric field [9]. Large magnetoresistance (MR) has also been reported in monolayer graphene nanoribbons [18].

Much attention has been recently paid to bilayer graphene which consists of two parallel graphene sheets coupled each other with two sublattices *A* and *B*, in each layer. They are typically stacked in *AB* Bernal form as shown in Fig. 1 leading to some interesting physical phenomena. For example new type of quantum Hall effect [19] and also the energy band gap tunable by vertically applied electric field are of its peculiar properties when compared to monolayer graphene [20–23].

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http://dx.doi.org/10.1016/j.jmmm.2014.01.011

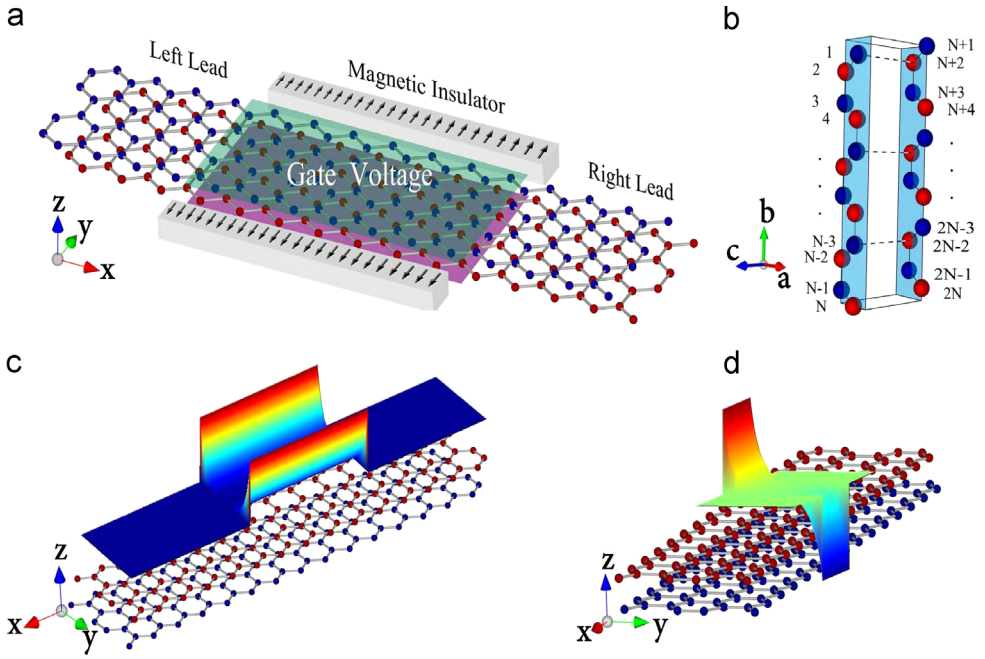

Fig. 1. (a) Schematic geometry of two-terminal structure for zigzag bilayer graphene nanoribbon (ZBGN) in the *AB* Bernal stacking. (b) Unit cell of the central region and the left and right electrodes. The unit cell consists of $2N$ atoms. Two ferromagnetic strips are attached to the edges of nanoribbon which induce exchange field in ZBGN. The direction of magnetization of strips can be parallel or antiparallel along the direction perpendicular to the graphene sheet. The induced magnetic potential M exponentially decays from the ribbon edges toward its middle. The induced magnetic field is arranged as (c) the parallel configuration or (d) the anti-parallel configuration of the edge magnetization. The decaying length of the induced magnetic potential is 1/3 of the ribbon's width.

A 200 meV band gap for bilayer graphene has been proposed by optical measurements and also theoretical predictions. Recently, an electrically tunable band gap has been observed in trilayer graphene with *ABC* crystallographic stacking [24]. Controllable band gap introduces bilayer graphene as an excellent candidate for spintronic devices [25]. The same as monolayer graphene, in the resonant bound states of the barrier, large spin polarization and also giant magnetoresistance have been reported in bilayer graphene in the limit of infinite width [26–28]. Motivated by the above mentioned studies we consider spin polarization and magnetoresistance in bilayer graphene nanoribbon with zigzag edges.

Mostly, FM insulator layers are deposited on top or bottom of BLG. However, simultaneous application of a perpendicular electric field which can be manipulated by means of the top-gate electrodes affects the induced exchange field arising from a FM insulator layer. In this work, the exchange field is induced by the FM insulator strips deposited on the ribbon edges while a perpendicular electric field is applied by means of the top-gate electrodes. This structure is more realistic from the experimental point of view. So we have to deposit the gate electrodes separate from the FM insulator strips. A schematic cartoon of our considered system is shown in Fig. 1 which contains the *AB* stacking of bilayer graphene nanoribbon accompanied with two strips of ferromagnetic insulator such as *EuO* deposited on two edges of nanoribbon. The direction of magnetization of the strips can be essentially justified in the parallel or antiparallel configurations. The induced exchange field is directed to perpendicular of graphene sheet. To simulate more realistic situation, we suppose that the edge-induced magnetic potential exponentially decays from the edge toward the middle of nanoribbon. In the tight-binding model, we use Landauer–Buttiker formalism to calculate the spin-dependent conductance. We have found large spin polarization and magnetoresistance when a band gap is opened in the anti-parallel configuration. The energy range in which spin polarization and magnetoresistance are large can be extended by application of a perpendicular gate voltage. Based on this behavior, one can manipulate a spin filed effect transistor.

The paper is organized as follows: in Section 2, we introduce the model and Landauer–Buttiker formalism for calculating conductance. The numerical results and discussion about spin dependent conductance and spin filtering and also magnetoresistance are presented in Section 3. Violation of parity conservation in bilayer graphene nanoribbons with even number of zigzag chains in width is presented in Section 4. Finally a conclusion of contents is presented in Section 5.

2. Hamiltonian and formalism

We consider a bilayer graphene nanoribbon with Bernal stacking (*AB*) which is connected to the left and right electrodes as indicated in Fig. 1. The total Hamiltonian, **H**, of the device can be divided into four parts as H_C, H_L, H_R, H_T which are the Hamiltonian of the center region, the left and right electrodes, and also the coupling Hamiltonian, respectively. The electrodes are considered to be the same as the central portion. The model is the tight-binding nearest-neighboring approximation with one π orbital per each site on the lattice. The effective Hamiltonian of bilayer graphene in the presence of magnetic strips is given as follows:

$$\begin{aligned} H_{C,\sigma} = & \sum_{l,i}(\varepsilon_{l,i}+\lambda_\sigma M_{l,i})a^\dagger_{l,i,\sigma}a_{l,i,\sigma}+\sum_{l,i}(\varepsilon_{l,i}+\lambda_\sigma M_{l,i})b^\dagger_{l,i,\sigma}b_{l,i,\sigma} \\ & -t\sum_{l,\langle i,j\rangle}(a^\dagger_{l,i,\sigma}b_{l,j,\sigma}+H.C.) \\ & -t_\perp\sum_{\langle i,j\rangle}(a^\dagger_{1,i,\sigma}b_{2,j,\sigma}+H.C.) \end{aligned} \quad (1)$$

$$\begin{aligned} H_{\alpha=L,R} = & \sum_{l,i}\varepsilon_{l,i,\sigma}(a_{l,i,\sigma}a^\dagger_{l,i,\sigma}+b_{l,i,\sigma}b^\dagger_{l,i,\sigma}) \\ & -t\textstyle\sum_{l,\langle i,j\rangle}(a^\dagger_{l,i,\sigma}b_{l,j,\sigma}+H.C.) \\ & -t_\perp\textstyle\sum_{\langle i,j\rangle}(a^\dagger_{1,i,\sigma}b_{2,j,\sigma}+H.C.) \end{aligned} \quad (2)$$

where $(a^\dagger_{l,i,\sigma})$ and $(a_{l,i,\sigma})$ and $(b^\dagger_{l,i,\sigma})$ and $(b_{l,i,\sigma})$ are creation and annihilation operators of an electron with spin $\sigma(\sigma=\uparrow,\downarrow)$ in the sublattice $A(B)$ in the layer $l=1,2$ at the ith site respectively. The onsite energy is indicated by $\varepsilon_{l,i}$. Here, $\lambda_\sigma=\pm1$ for $\sigma=\uparrow,\downarrow$. The