Effects of Rashba spin-orbit coupling on the conductance of graphene-based nanoribbons

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The transmission properties of armchair- and zigzag-edged graphene nanoribbon junctions between graphene electrodes are examined by means of the standard nonequilibrium Green’s function (NEGF) technique. The quantum transport of electrons is studied through a monolayer graphene strip in the presence of Rashba spin-orbit coupling that acts as a barrier between the two normal leads. The present work compares the conductances of nanoribbons with zigzag and armchair edges. Since the nature of induced gap for zigzag edge is different from armchair, it is expected to give rise to different types of conductance for each edge. Findings indicate that the Rashba strength has more pronounced influence on armchair ribbons than on zigzag ribbons, and the minimum conductance of $2G_0$ for nanoribbon remains intact even in the presence of the Rashba spin-orbit coupling. It is predicted that controllability of spin transport in the monolayer graphene may contribute to the development of well-known spintronics.

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1. Introduction

The lack of bandgap in graphene hinders its application in technology and industry in spite of its many intriguing and unique properties. One strategy for inducing gap for the monolayer graphene is to produce a one-dimensional graphene strip, namely, the graphene nanoribbon (GNR).¹

Nanoribbons are obtained by cutting a stripe out of the two-dimensional (2D) graphene sheet along a specified direction. Practically, graphene nanoribbons are

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available from the chemical route\textsuperscript{2} or the longitudinal unzipping of carbon nanotubes.\textsuperscript{3} Based on the shape of the confining edges, two main types of nanoribbons with zigzag (ZGNR) and armchair (AGNR) terminations were obtained with quite different transport properties. The peculiarities of nanoribbons have drawn many interesting studies on their electronic,\textsuperscript{4–8} magnetic\textsuperscript{9–12} and transport properties.\textsuperscript{13,14} Another method for inducing bandgaps in energy bands deals with the presence of spin-orbit interaction (SOI) in the material. There are two possible types of SOIs in the graphene: intrinsic and Rashba (R). The intrinsic SOI opens a gap in the energy spectrum and transforms graphene into a two-dimensional topological insulator.\textsuperscript{15} However, the intrinsic SOI is extremely weak in pristine graphene.\textsuperscript{16,17} The extrinsic Rashba spin-orbit coupling (RSOC), which arises from breaking the mirror symmetry of the graphene plane, can be very large for graphene grown on a substrate.\textsuperscript{18,19} 

In Ref. 20, conductances of spin and electron in a parallel and antiparallel graphene-based ferromagnet–superconductor–ferromagnet (FSF) and ferromagnet–superconductor (FS) junctions have been studied, and Ref. 21 has focused on the electronic transport properties of topological insulator-based ferromagnetic–normal–ferromagnetic (FNF) and topological insulator-based ferromagnetic–barrier–ferromagnetic (FBF) junctions on the surface of topological insulator in low temperature and clean regimes. Reference 22 deals with the effects of parallel and antiparallel alignment strengths of ferromagnets, thickness of normal region and temperature on the charge, spin and thermal conductances in graphene-based ferromagnetic–normal–ferromagnetic junctions, the electronic transport in GNR junctions and GNR with partial edge cutting has been studied numerically, and results show that the ribbon width is expected to be narrower than 10 nm for observing the zero conductance dips at room temperature.\textsuperscript{23} Graphene Josephson junctions have been designed with different edges and showing that the dependence of the critical supercurrent on the superconducting arbitrary width is drastically different for different types of edges.\textsuperscript{24} Experimental studies focusing\textsuperscript{25} on the impact of line-width scaling on the GNR transport showed that for the GNR width less than 60 nm, carrier mobility in GNRs is limited by edge-scattering. The Josephson current in a graphene-based superconducting quantum point contacts with length $L$ smaller than the superconducting coherence length and an arbitrary width $W$, is not quantized for the nanoribbons with smooth and armchair edges. For a zigzag nanoribbon, however, it is quantized.\textsuperscript{26} Also a number of studies have been done on the transport in GNR with Rashba SOI (RSOI) and zigzag edges. For example, Zarea and Sandler\textsuperscript{27} analytically derived the energy spectrum of a zigzag GNR with RSOI which is produced by an electric field perpendicular to the GNR surface. Gosalbez-Martinez et al.\textsuperscript{28} studied the RSOI produced by the effects of curvature in zigzag GNRs. In the paper,\textsuperscript{29} the focus was on the influence of RSOI on the spectrum and the spin polarization of AGNR. Cao et al.\textsuperscript{30} have investigated the transport properties of a zigzag graphene in two cases. One case is when both the magnetization and the
Rashba SOC effect exist in the central region, and the conductance modulated by the Rashba strength behaves as switch. Another case is when two zigzag ribbon electrodes are ferromagnetic while the central region is nonmagnetic. They found that in the presence of the Rashba spin-orbit coupling and the magnetization becomes evident an energy gap in the band structure of the central region and the conductance of the system can be tuned by the strength of the Rashba SOC. Recently, Kariminezhad and Namiranian have studied the spin-dependent conductance as a function of the RSOI strength for different $N_y, N_x$ and Fermi energy values ($E_f$) in zigzag graphene nanoribbons. They consider an unrealistic parameter range for the Fermi energy and for the magnitude of the Rashba interaction because the accessible Fermi energy in real systems is only a small fraction of the bandwidth. The range of Fermi energies up to 30% of bandwidth $t$ is unrealistic, and the realistic values for the magnitude of the Rashba interaction are smaller than 1%. They found that the spin conductance depends on the width and length of the graphene nanoribbons in the limit of large Rashba spin-orbit interaction strength.

The conductance is not quantized in the presence of Rashba coupling in monolayer graphene with bulk geometry coupling. When the Rashba spin-orbit strength is zero ($\lambda = 0$), the conductance has its full value. By increasing the strength of the Rashba spin-orbit coupling $\lambda/E_f$, the conductance decreases in a way that it reaches zero at $\lambda = E_f$. In the range of $\lambda > E_f$, the conductance begins to increase and reaches to a saturation value. Conductance can be turned on or off by adjusting the Rashba spin-orbit coupling in this junction.

The present study deals theoretically with the conductance of an armchair (zigzag)-terminated graphene nanoribbons between two semi-infinite AGNR (ZGNR) electrodes by means of the nonequilibrium Green’s function (NEGF) technique. The assumption is that the Rashba SOI occurs just in the central region between reservoirs. Findings indicate that the Rashba strength has more pronounced influence on the armchair ribbons than on the zigzag ribbons.

2. System and Model Hamiltonian

The present study considers a graphene device extended in the $xy$-plane. It is composed of a central graphene nanoribbon with RSOI being sandwiched between two semi-infinite graphene nanoribbon leads as depicted in Fig. 1. The region with the Rashba spin-orbit coupling covers the middle region from $x = 0$ to $x = L$. The kinetic Hamiltonian in the tight-binding approximation that is restricted to the nearest neighbor is given by

$$H = -t \sum_{ij} \sum_\sigma \{b_{i\sigma}^+(R_i + d_j)a_{\sigma}(R_i) + h.c.\},$$

where $a_{\sigma}(R_i)$ annihilates a quasiparticle on the A atom at lattice position $R_i$ with spin $\sigma$, $b_{i\sigma}^+(R_i + d_j)$ creates a quasiparticle at the B atom in the $R_i + d_j$ site with spin $\sigma$ and $t$ is the hopping energy. $d_j$ is the displacement vector. The RSOI Hamiltonian