Spin-dependent transport through hybrid ferromagnet-graphene rings

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Abstract

Due to its large electron mobility and long coherence lengths, graphene is a material of choice to study quantum coherence phenomena, such as the Aharonov-Bohm effect. The observation of Aharonov-Bohm conductance oscillations in a graphene ring [1] suggests that quantum interference effects can be used to design novel nanodevices. In this context, Wu *et al*. have demonstrated theoretically that rectangular graphene nanorings pierced by a magnetic field behave like a resonant tunneling device [2]. Hung Nguyen *et al*. reported a numerical study on the transmission probability in rectangular rings and concluded that it can be strongly modulated and fully suppressed when tuning the magnetic field [3].

Recently, we have studied electron transport in the fully coherent regime through a quantum interference device based on a hexagonal graphene nanoring [4], in which all edges are of the same type to reduce scattering at bends [5]. We demonstrated that electron transport can be controlled by a side gate voltage applied across the nanoring. Moreover, the hexagonal ring operates as an efficient spin filter if a layer of a ferromagnetic material, such as, EuO is deposited on top of it [6]. The filtering effect results from the proximity exchange interaction between Eu^{2+} ions and graphene electrons [7,8]. In Ref. [6] we discussed the impact of imperfections on the spin filtering efficiency of the hexagonal ring. We also considered asymmetric rings with one arm wider than the other and found out that the polarization sign can be switched much more abruptly, making an asymmetric design more advantageous for applications. In this work we address asymmetrically connected square nanorings .

The quantum transmission boundary method combined with the effective transfer matrix approach were used to calculate wave functions and spin-dependent transmission coefficients for spin up ($T_\uparrow$) and spin down ($T_\downarrow$) electrons (see Ref. [6] for further details). We define the degree of transmission polarization as $P = (T_\uparrow - T_\downarrow)/(T_\uparrow + T_\downarrow)$ and it will be the figure of merit to assess the spin filtering efficiency.

We compare the transmission properties of symmetric and asymmetric rings with semiconducting leads (nanoribbons with armchair borders, which have an energy gap) in the absence of proximity exchange interaction. We have numerically found that the transmission patterns can be grouped into two categories, depending on the value of the nanoribbon width w. If the number of hexagons is of the form $N = 3n - 2$, n being an integer, the transmission coefficient presents resonant peaks whose shape is Lorentzian close to the resonance energy. A typical example is shown in Fig. 2(a) corresponding to w = 10.6 nm ($N = 43$), for both symmetric (dashed line) and asymmetric (solid line) rings. When $N = 3n$, the transmission coefficient strongly depends on the symmetry of the ring. As shown in Fig. 2(b) for w = 11.1 nm ($N = 45$), the transmission coefficient for symmetrically connected rings is rather smooth and increases uniformly in the one-mode energy windows (dashed line). On the contrary, if the ring is connected asymmetrically, the transmission coefficient presents Fano-like antiresonances (solid line).

When the EuO layer is deposited on top of the ring, the interaction with the ferromagnet shifts the transmission curves towards upper energy for spin up electrons or towards lower energy for spin down electrons. The energy shift is of the order of 5 meV. Except for the energy shift, the transmission pattern remains qualitatively the same and is not shown here while the transmission polarization is presented in the lower panels of Fig. 2. For symmetrically connected rings, the transmission polarization P changes sign smoothly over a wide energy region. Consequently, transmission polarization remains rather insensitive to changes of the Fermi energy. On the contrary, the polarization for asymmetrically connected rings changes more abruptly, especially in the case $N = 3n$, and therefore it can be controlled by small changes of control parameters, which can be useful for applications.

In summary, we have proposed and studied a novel spin filter which exploits quantum interference effects. The proximity induced exchange interaction between ferromagnetic ions and electrons in graphene can be exploited to obtain a spin-dependent transmission coefficient and, as a consequence, a spin-dependent conductance We found that the polarization of the transmission changes more abruptly with the Fermi energy in asymmetrically connected rings due to the occurrence of Fano-like antiresonances.

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Figures

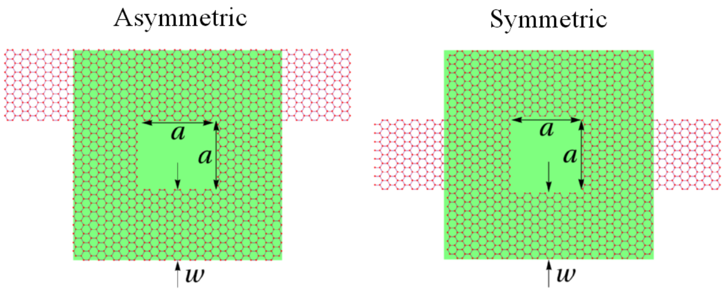

Figure 1. Schematic view of graphene nanorings connected symmetrically or asymmetrically to two armchair nanoribbons. The ferromagnetic insulator layer is grown on top of the nanorings.

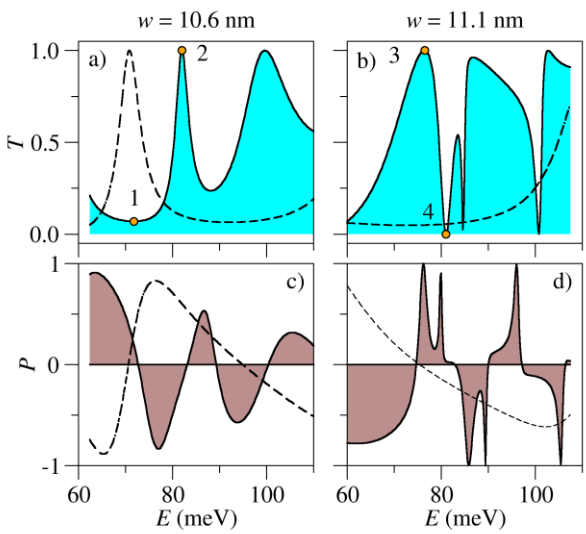

Figure 2. Upper panels show the transmission coefficients in the absence of ferromagnetic layer for two different values of the nanoribbon width (given in the plot). Lower panels show the transmission polarization when the ferromagnetic layer is grown on top on the nanoring. Solid and dashed lines correspond to asymmetric and symmetric rings, respectively..