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Effects of external magnetic fields and Rashba spin-orbit coupling on spin conductance in graphene

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ABSTRACT

The present article is concerned with spin conductance in graphene (SCG) when *both* the application of an external magnetic field and Rashba spin-orbit coupling (RSOC) are taken into account. Introducing a Casimir operator, we analyze the structure of total Hamiltonian and demonstrate how the matrix elements along with the summations involved in the suitably adopted Kubo's formula, may be analytically calculated. From the results so-obtained one finds that, in addition to discrete and symmetric behavior of SCG against the external field, it exhibits large peaks as high as six times that in ordinary two dimensional electron gases. Moreover, it is shown that for any Fermi energy the SCG asymptotically approaches a value three times larger than the standard unit of $(e/4\pi)$, for large magnetic fields. Effects of the magnetic field, RSOC and Fermi energy on the characteristics of SCG are also discussed. The material presented in this article thus provides novel means of controlling the SCG by external agents.

1. Introduction

In recent years it has become vividly established that spintronic devices form the corner-stone of future information technology [1–3] . The basic idea behind the development of the semiconductor spintronics is the generation of spin currents (instead of charge currents), with the natural obstacle of spin-decoherence, i.e., dissipations [4–8]. It is thus of great importance to explore means of production and control of least dissipative spin currents. In this regard and due to its unique and remarkable

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properties, in particular, long spin diffusion length [9,10], high-efficiency spin injection [11–13], etc. [14,15], graphene has attracted much research interest.

The notion of spin currents, induced by electric fields, was introduced in early seventies [4] and has been the subject of numerous experimental and theoretical reports [16–19]. It is a basic fact that for spin states to separate and thus to produce spin currents, the time-reversal symmetry should be broken. Breaking of time-reversal symmetry occurs whenever spin-orbit couplings (SOC) and/or magnetic fields act in the system [20,21]. To this end, the system of two dimensional electron gas formed at the interface of GaAs/AlGaAs, in which the Rashba spin-orbit coupling (RSOC) is the prominent contributor to the spin current has been extensively investigated [22,23]. However, since the free π-electrons behave as massless Dirac particles, a larger spin conductance is expected to occur in graphene. This point is supported by the fact that, for instance, the π-electron mean free path of 400 nm s is about five times larger than that in GaAs [24–26].

Graphene, a two-dimensional sheet of graphite with honeycomb structure, exhibits unique properties, much different compared with ordinary two dimensional materials [27,28]. Such remarkable properties stem from the fact that the so-called π-electrons acquire a linear energy spectrum around the Dirac points in the Brillouin zone [29]. It then turns out that the lattice sites, formed by identical carbon atoms, play the role of pseudospin states [29,30]. Consequently, one encounters the well-known abnormal quantum Hall effect [29,31,30,32]. It is due to such incredible properties that nano scale structures, i.e. nanoribbons, nanodots, etc., made of graphene have been suggested for practical implementation of spintronics devices. Specifically, one could mention applications in quantum computers [33], quantum communication channels [34,35] and so forth [36]. The present article is thus devoted to a thorough examination of spin conductance (spin Hall conductance) in graphene (SCG) under the influence of *both* the RSOC and external magnetic fields.

In the absence of magnetic fields SOC forces the spin states to separate, giving rise to spin currents in a natural way. The SOC in graphene [37,38] consists of intrinsic and extrinsic components. The intrinsic component is rather weak in plane graphene [41,42] but grows to considerable magnitudes in nano scaled graphene [39,30]. Although the intrinsic SOC leads to a very small gap and quantized spin conductance [39,40], in what follows we shall ignore the effect of the intrinsic SOC. On the other hand, the extrinsic one, known as the Rashba spin-orbit coupling [43], can become much stronger, depending upon the substrate on which graphene is grown [44]. This fact was recently reported for the single layer of graphene on Ni(1, 1, 1) intercalated by Au [45]. It has also been demonstrated that the RSOC may be tampered by the application of external electric fields (gate potentials) [46,47]. This point also justifies the ignorance of intrinsic SOC. In the material presented in this paper, we complement the reports in Refs. [48–52] by considering, in addition to RSOC, the influence of an external magnetic field applied normal to graphene. The simultaneous presence of both effects, as we shall show, leads to a drastic enhancement in SCG. In fact we demonstrate that under specific conditions placed on the Fermi energy (FE), external magnetic field and RSOC parameter, peaks of about six times larger than previously reported [50] occur in SCG. In this connection and since both the magnetic field and RSOC are externally controllable in what follows the role of each is distinguished and discussed.

The present report is organized in the following manner. After introducing the subject under consideration, the model and the Hamiltonian, along with the π-electron's states, are given in Section 2. Section 3 is devoted to the determination of SCG, followed by a thorough discussion of the results in Section 4. We conclude the article by summarizing the results in Section 5.

2. The model

The π-electron in graphene is described in a Hilbert space, $\mathcal{H} = \mathcal{H}_c \otimes \mathcal{H}_s \otimes \mathcal{H}_p$, where $\mathcal{H}_c, \mathcal{H}_s$ and $\mathcal{H}_p$, are, respectively, the configuration, the pseudospin and ordinary spin Hilbert spaces. The elements of $\mathcal{H}_c$ are $\vec{p} = -i\hbar\nabla$, those of $\mathcal{H}_p$ are $\sigma_i (i = x, y)$ that act on the lattice sites $|A(B)\rangle$, while the elements in $\mathcal{H}_s$ are $s_i (i = x, y, z)$ acting upon the bases $|\pm\rangle$. The Hamiltonian of the π-electron, around the Dirac points, is then given by the 4×4 matrix [30].

$$H = v_f(\vec{\sigma} \cdot \vec{p}) + \frac{\lambda}{2}(\vec{\sigma} \times \vec{s})_z, \tag{1}$$