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Exact solutions of the extended spin field-effect transistor

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ABSTRACT

Transmission oscillations of the ballistic spin transport through an extended spin field-effect transistor (SFET) are investigated. To the system of the normal incident electrons passing through the SFET between two normal leads, the transmission coefficients and the corresponding Landauer–Büttiker conductance can be obtained analytically. From the results it can directly find that the transport properties are obviously modulated by the spin of the incident electrons, the type and intensity of the spin–orbit coupling, the potentials strength, as well as the width of the SFET.

1. Introduction

Since the prominent spintronic device, the spin-field-effect transistor (SFET) was first proposed by Datta and Das [1]. related researches have been extensively done to realize its function [2–11]. As one of the typical ballistic quantum systems, the ferromagnetic/semiconductor/ferromagnetic (F/S/F) double junction has been attracted many research interest for its fundamental importance and potential microelectronic applications [12–16]. In such novel spintronic devices, it is usually used the Bychkov and Rashba [17] spin–orbit coupling (SOC) to perform controlled the spin rotation of electrons passing through the system. This particular SOC is due to the structure inversion asymmetry (SIA) of the confining potential [18], which can be controlled by a gate voltage applied perpendicular to the two dimensional electron gas (2DEG) [2]. Exactly, for lots of materials, the electrons are not only subject to the Rashba SOC, but also to the Dresselhaus SOC [19], which is present in semiconductors lacking

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bulk inversion symmetry (BIA) [20,21]. Sometimes the two SOCs can even be comparable, so it is viable to take into account both of them in the related electron transports [13,22,23].

Ballistic spin transport in two-dimensional F/S/F devices due to the SOC has been extensively studied. It demonstrates that the Rashba SOC in semiconductor heterostructures can produce and control a spin-polarized current without ferromagnetic leads [9,24], and even in some special SOCs the original device can be formed [8]. As the ballistic spin field-effect transistors, Jiang et al. [25] investigate the conductance modulations by taking into account the effect of the Rashba SOC, interface scattering, the presence of a in-plane magnetic field, band mismatch, as well as the unparalleled magnetization of the two ferromagnetic electrodes. In earlier time, Lee and Choi [14] have reported the ballistic transport through a two-dimensional mesoscopic double junction in presence of the SOCs, and they show that the Rashba and Dresselhaus terms can induce finite transverse and longitudinal spin currents. Recently, we have studied the double refraction of spin-polarized electron entering from a non-Rashba region to a Rashba region within the 2DEG [26], the extended SFET [27], and obtained some analytical expression for the whole transport. From these works they show that the ballistic transport of the SFET is very important. So it will be necessary to get the prototype calculations of the SFET and show some interesting and important characters of the transport.

In this work, by taking into account both the Rashba and Dresselhaus SOC (R–D SOC), the transport properties of the SFET are investigated. We mainly obtain the exact solutions of the transmission and the conductance in the case of the normal incidence. And the electron charge-current density in the x direction, effect of the R–D SOC to the charge-current density, the transmission probability and the conductance are discussed in detail.

2. Model and formulations

To investigate the electron transport of the Datta–Das SFET, we consider a two-dimensional electron system as sketched in Fig.1. The energy eigenvalues of an electron confined in the plane can be obtained by solving the Schrödinger equation with the Hamiltonian characterized by the R–D SOC, and the eigenenergy relies on the strength of the two types of SOC and the width of the SOC affected region (labeled as Region S). The first and third regions are the source and drain leads respectively, in which no SOC is present and the free electron model is justifiable (labeled as Region L and Region R). When a normal or oblique-incidence electron passes through the SFET, its motion depends upon the momentum and spin-state of the electron as a result of the SOC, which can be described as the electronic double refraction. In the effective mass approximation, the Hamiltonian of an electron moving in the SOC region (Region S) takes the form [13,22,26]

$$\hat{H}_S = \frac{\hat{p}_x^2 + \hat{p}_z^2}{2m_s} + \frac{\hbar k_\alpha}{m_s}(\sigma_z \hat{p}_x - \sigma_x \hat{p}_z) + \frac{\hbar k_\beta}{m_s}(\sigma_z \hat{p}_z - \sigma_x \hat{p}_x) + V(x), \tag{1}$$

where $\hat{p}_x,\ \hat{p}_z$ and m_s are the momentum operator in the x and z planes and the effective mass of an electron in Region S, $\hbar$ is the Plank constant. k_α and k_β are defined as $k_\alpha = \frac{m_s \alpha}{\hbar^2},\ k_\beta = \frac{m_s \beta}{\hbar^2}$, with α and β the strength of the Rashba and Dresselhaus effect respectively, which are assumed to be zero in the Region L and R ($x < 0$ or $x > L$) and positive constants in Region S ($0 < x < L$). $\sigma_{x/z}$ are the Pauli matrices, and $V(x) = U[\delta(x) + \delta(x - L)]$ is the delta interfacial potentials.

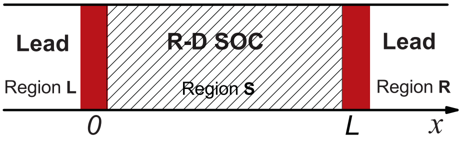

Fig. 1. Schematics of the spin-field-effect transistor (SFET). The left and right blank regions are the source and drain leads made of normal metals respectively. The middle shadowed region is subjected to the R–D SOC.