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Spin filtering and spin diode devices in quantum wire systems

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Abstract

Theoretical studies on the spin-dependent transmission and current–voltage characteristic in a mesoscopic system, which consists of two semi-infinite ferromagnetic (FM) leads (as source and drain) separated by a typical periodic quantum dot (QD) are presented. The calculations are based on the tight-binding model and transfer matrix method, and investigate the magnetoresistance (MR) and the spin polarization within the Landauer–Büttiker formalism. The spin-dependent transport behavior can be controlled via a gate voltage and an applied bias in the ballistic regime. The numerical results are shown for a periodic polymer chain with nonmagnetic (NM) and FM leads, and also, with two FM leads. The first system (NM/QD/FM) acts as a spin-filter device in a special condition also contact as a spin diode device. The application of the predicted results may be useful in designing molecular spin-polarized transistors in the future.

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Keywords: Spin filter; Magnetoresistance; Quantun dot (QD)

1. Introduction

During the past few years, much effort has been made for better understanding the physics of spin-dependent transport in magnetic junctions. The most important reasons for this are due to discovery of the nanofabrication techniques, in materials science [1–4], and the possibility of its application in digital storage [5] and magnetic sensor technologies [6]. The magnetic structures consisting of two ferromagnetic (FM) layers separated by a thin insulating barrier layer exhibit a large tunneling magnetoresistance (TMR) effect [7,8]. TMR is commonly modulated by the relative orientation of the magnetizations of the two FM electrodes, which can be changed by an applied magnetic field. The origin of TMR can be explained by imbalance in the transmission probability for up- and down-spin electrons through the barrier in the magnetic junctions, which depends on its Fermi wavevectors in FM electrodes. Due to the exchange

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splitting in band structure of a FM, the up- and down-spin electrons have different wavevectors, and consequently, a tunneling probability that depends on the spin [9,10].

One of the most important spin-based electronic devices is a mesoscopic quantum dot (QD) system [11,12], which has typical dimensions between nanometers to a few microns [12–14]. The size and shape of these structures and therefore the number of electrons they contain, can be precisely controlled. The physics of QDs is corresponding with behavior of naturally occurring quantum systems in atomic and nuclear physics. As in an atom, the energy levels in a QD become quantized due to the confinement of electrons, then quantum correlation effects induce localization. Unlike atoms, however, QDs can be easily connected to electrodes and are therefore excellent tools to study atomic-like properties. A QD can have anything from a single atom to a collection of several molecules.

Spin-dependent transport through a QD system, has been investigated recently [15–18] by coupling it to the magnetic leads and passing current through the dot. In this new type of the magnetic junctions, a QD device, instead of the usual insulator layer (as in the standard TMR setup) is used in between the FM leads. The obtained results depend on the configuration of the QD device, which may be useful in designing future molecular wires and spin-polarized tunneling devices for electronic applications [19].

In this paper, we demonstrate the spin-polarized transport of the transmitted electrons through a molecular chain (as a type of the QD device), due to the magnetic properties of the leads in the magnetic structures composed of the NMQD/FM and FM/QD/FM junctions. In the model, we have assumed the spin diffusion length is larger than the size of the device, so that no spin scattering takes place within the device. Using the transfer matrix method [20–24] and the tight-binding model in the Landauer–Büttiker formalism [25], the effect of the bias voltage and the gate voltage on the magnetoresistance (MR) and spin polarization of the transmitted currents at $T = 0\,\mathrm{K}$ are investigated. We show that our device can act as a perfect spin filter or also as a spin diode under special conditions on the leads and the QD.

The organization of this paper is as follows. In Section 2, the tight-binding one-electron Hamiltonian is described. Also, a detailed description of the transfer matrix approach of the spin-dependent transport though the considered junctions are given. In Section 3, the numerical results for the transmission coefficient, the MR and spin polarization of the transmitted current are discussed. Concluding remarks are summarized in Section 4.

2. Theoretical model

In this work, we study the spin transport properties of the passing electrons in (FM or NM)/QD/FM structures, in the presence of a applied bias V_a. In this formulation, electrons are assumed to be incident on a sample that in connected to two magnetic semi-infinite ideal leads via the QD. For simplicity, we assume the two FM electrodes are made of the same material and also, the QD is formed by two different atoms A and B, which have the on-site and hopping energies only. Moreover, no diffuse scattering is introduced at the interfaces. The schematic profile of junctions for this case is shown in Fig. 1.

The full Hamiltonian for description of the structure is given by

$$H = H_L + H_{DL} + H_D + H_{DR} + H_R, \tag{1}$$

where $H_{L,D,R}$ describes the Hamiltonian for the isolated left (L) lead, dot (D), and right (R) lead.

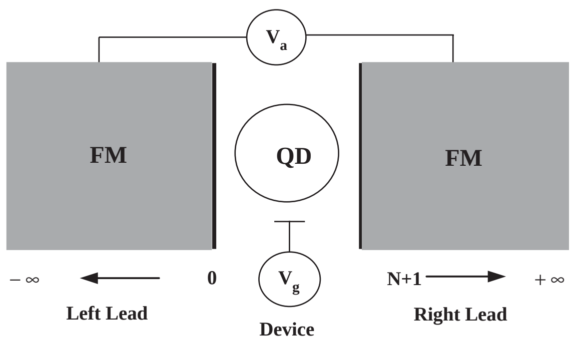

Fig. 1. Spin-dependent potential schematic for FM/QD/FM magnetic junction under forward bias V_a.