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Spin-polarized transport in a δ-doped magnetic-barrier nanostructure

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ABSTRACT

We theoretically investigate the electron spin transport properties through a δ-doped magnetic-barrier nanostructure, which can be realized experimentally by depositing two identical ferromagnetic stripes with the opposite in-plane magnetization on the top of a semiconductor heterostructure in parallel configuration and by using atomic layer doping technique. The δ-doping dependent transmission, conductance and spin polarization are calculated exactly by analytically solving Schrödinger equation of the spin electron. It is found that the electronic spin-polarized behavior in this device can be manipulated by changing the weight and/or the position of the δ-doping. Therefore, such a device can be used as a controllable spin filter, which may be helpful for spintronics applications.

1. Introduction

It is well-known that, by confining the motion of a two-dimensional electron gas (2DEG) (formed often in a modulation-doped semiconductor heterostructure) with an inhomogeneous magnetic field on the nanometer scale, e.g., depositing nanosized ferromagnetic stripe on the top of the semiconductor heterostructure, the so-called magnetically modulated semiconductor nanostructure (MMSN or magnetic nanostructure) [1] can be fabricated in experiments. This kind of nanostructure is actually the hybrid of the magnetic material and the semiconductor, which the former provides an inhomogeneous magnetic field locally influencing the motion of the electron in the latter [2]. Due to the low dimensionality, the small size and the magnetic confinement, the electronic transport in a magnetic nanostructure has been a hot focus for the theoretical and experimental researchers [3]. Many interesting transport properties, such as the wave vector filtering [4] and giant magnetoresistance effect [5,6], have been reported.

Recently, the spin-dependent transport in the magnetic nanostructure has attracted much current attention, because of its potential application in realizing spin injection into the semiconductor [7]. The internal magnetic field in a magnetic nanostructure generates the Zeeman coupling or the spin–field interaction with the intrinsic spin of the electron, which makes the spin injection into semiconductor material become possible [8]. Initially, Papp and Peeters [9] studied the spin polarization in a magnetic nanostructure created [10] by depositing a ferromagnetic (FM) stripe with a horizontal magnetization and under a negative DC volts on the top of the semiconductor heterostructure in experiments, and found that such a magnetic nanostructure can serve as a spin filter. Unfortunately, a error appeared in their numerical calculation [11], which led up to incorrect results [12,13]. Subsequently, the spin polarization in another magnetic nanostructure, formed experimentally by depositing two FM stripes with the opposite horizontal magnetization on the top of the semiconductor heterostructure, was investigated by Xu and Shi [14] and nearly 100% spin polarization was found in such a magnetic nanostructure [15]. Realistic magnetic nanostructure produced by lithographic patterning of ferromagnetic or superconducting film were considered severally by Lu et al. [16] and Zhai and Xu [17] and the general rule of the spin polarization were revealed in this type of magnetic nanostructures. For the hybrid magnetic nanostructure fabricated by depositing one FM stripe with the aclinic magnetization and one Schottky-metal (SM) stripe in the parallel configuration, Zhai et al. [18] explored the spin polarization in this kind of magnetic nanostructures and found that its degree can be tuned by changing the voltage on the SM stripe. The spin polarization is also reported successively in other magnetic nanostructures formed by depositing two FM stripes on the top and the bottom of the semiconductor heterostructure, and some spin filters are proposed successfully [19–21].

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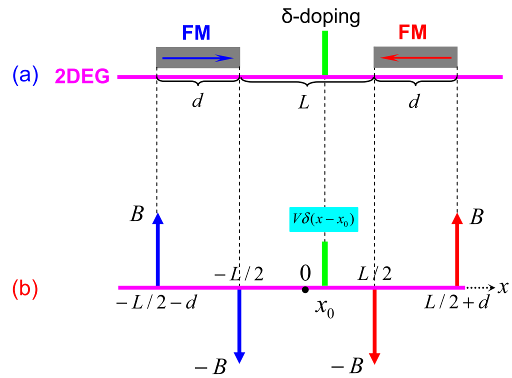

Fig. 1. (a) Schematic illustration of the magnetic nanostructure, where two identical FM stripes with opposite magnetizations in parallel configuration deposited on the top of the semiconductor heterostructure and the δ-doping is comprised by the atomic layer doping technique, and (b) the magnetic profile and the δ-doping in magnetic nanostructure.

Very recently, to control the spin-polarized electron in the magnetic nanostructure, a idea to structurally manipulate the spin polarization by the atomic layer doping technique [22] has been proposed theoretically. Utilizing such a technique such as molecular beam epitaxy (MBE) [23], a tunable δ-potential can be intentionally doped into a magnetic nanostructure, called δ-doped magnetic nanostructure. Of necessity, the electronic transport in this kind of nanostructure will be related to the δ-doping, in other words, the spin polarization in the magnetic nanostructure should be controllable by the δ-doping [24]. The effect of the δ-doping on the spin polarization is systematically studied [25–27] in magnetic nanostructures, which are produced by depositing two FM stripes on top and bottom of a semiconductor heterostructure. Structurally manipulating the spin filtering also is reported [28,29] in magnetic nanostructures consisting of realistic magnetic barriers. Motivated by these works, in this paper, we explore the modulation of the δ-doping to the spin polarization in another δ-doped magnetic nanostructure.

2. Model and method

The δ-doped magnetic nanostructure under consideration, as is shown in Fig. 1, is a 2DEG, subject to the modulation of an inhomogeneous magnetic field and the δ-doping. Experimentally, this nanostructure can be fabricated by depositing two FM stripes in the parallel configuration on the top of a semiconductor heterostructure [30] and by exploiting the atomic layer doping technique. Here, the d is the width of the FM stripe, the L is the separation between two FM stripes, and for convenience we assume that the δ-doping with the weight V and the position x_0 is sandwiched between two FM stripes in the whole paper. The magnetic field experienced by the 2DEG in (x, y) plane can be written as

$$\begin{cases} \vec{B} = B_z(x)\hat{z}, \\ B_z(x) = B\big[\delta(x+L/2+d) - \delta(x+L/2) - \delta(x-L/2) + \delta(x-L/2-d)\big], \end{cases} \tag{1}$$

while the corresponding magnetic vector potential can be expressed, in Landau gauge, i.e., $\vec{A} = [0, A_y(x), 0]$ with

$$A_y(x) = \begin{cases} 0, & x < -L/2-d \\ B, & -L/2-d < x < -L/2 \\ 0, & -L/2 < x < L/2 \\ -B, & L/2 < x < L/2+d \\ 0, & x > L/2+d. \end{cases} \tag{2}$$

Thus, the Hamiltonian describes an electron moving along x direction in the above 2DEG nanostructure, within the effective mass approximation, is

$$H = \frac{p_x^2}{2m^*} + \frac{[p_y + eA_y(x)]^2}{2m^*} + \frac{eg^*\sigma\hbar}{4m_0} B_z(x) + V\delta(x-x_0), \tag{3}$$

where m^* and m_0 are the effective mass and the static mass of an electron, respectively, $\vec{p} = (p_x, p_y)$ the electronic momentum, g^* the effective Landé g-factor, and $\sigma = +1/-1$ is for spin-up/spin-down electron. It should be noticed that, FMs are often accompanied by an electric potential when they are deposited on the top of the heterostructure, i.e., in above equation the Hamiltonian should include such an electric potential item. Moreover, depending on the relative phase between the magnetic field caused potential and electric potential, this electric potential will play am important role in determining the spin-polarized transport property [9]. However, in order to give prominence to the effect of the δ doping on the spin filtering, in the present work we neglect it for the moment. In addition, for more convenient treatment we introduce two characteristic quantities, the magnetic length $\ell_B = \sqrt{\hbar/eB_0}$ and the cyclotron frequency $\omega_c = eB_0/m^*$ with a typical magnetic field B_0, then all the relevant quantities are written as the dimensionless form, e.g., $A_y(x) \to B_0\ell_B A_y(x)$, $x \to \ell_B x$ and $E \to E\hbar\omega_c$.

Because of the conserved motion of the electron along the y-axis in a magnetic nanostructure, the solution of the stationary Schrödinger equation $H\Psi(x, y) = E\Psi(x, y)$ can be expressed by $\Psi(x, y) = \psi(x)\exp(ik_y y)$, where k_y is the transverse wave vector. The