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Spin filtering in a hybrid ferromagnet, Schottky metal and semiconductor nanostructure

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ABSTRACT

We report a theoretical study of spin-dependent transport in a magnetic nanostructure, which can be experimentally realized by depositing a ferromagnetic metal (FM) stripe and a Schottky metal (SM) stripe on the top and at the bottom of the semiconductor heterostructure. Theoretical analysis reveals that the intrinsic symmetry in a single FM-stripe magnetic system can be broken by the SM stripe placed at the bottom of the heterostructure, and thus a sizeable spin polarization effect appears. Numerical calculation shows that not only amplitude of the spin polarization but also its sign varies with the width and/or the position of the SM stripe.

1. Introduction

How to spin polarize electrons into semiconductor materials has attracted much interest as the emerging research area of spintronics utilizes the spins of the electron to store and carry information [1]. So far, many alternative schemes have been proposed both theoretically and experimentally [2]. One of them is to exploit the magnetic nanostructure [3], which is experimentally realized by confining the motion of the two-dimensional electron gas (2DEG) (usually formed in a modulation-doped semiconductor heterostructure) with an inhomogeneous magnetic field on the nanometer domain, e.g., depositing nanosized ferromagnetic (FM) stripes on top of a semiconductor heterostructure [4]. In the magnetic nanostructure, there exists a precious magnetic field distribution, which can induce the spin splitting by the Zeeman interaction between the magnetic field and the electron-spins. Many magnetic nanostructures have been exploited to serve as spin filters for spintronics applications; see Refs. [5–12] for example.

A simple, experimentally attractive proposal for a spintronics device is to exploit one single FM stripe with the horizontal magnetization, deposited on the top of the semiconductor heterostructure. This device has been investigated widely [5,13–16], and many interesting results have been obtained by numerical calculations. However, no spin filtering can occur in this device [17,18] due to the antisymmetric magnetic profile and the symmetric magnetic vector potential pertaining to the center of this device, also referred to as an intrinsic symmetry [19]. In order to break such a symmetry in this device, Zhai et al. [20] proposed to place a Schottky metal (SM) stripe parallel to the FM stripe on top of the semiconductor heterostructure. Thereby, a sizeable spin polarization effect appears and this device can be used as a spin filter. Lu et al. [21] proposed to add another FM stripe with in-plane magnetization at the bottom of the semiconductor heterostructure, which gives rise to two δ-function magnetic barriers with nonidentical magnetic strength. As a result of this, the intrinsic symmetry is broken and this device shows up a considerable spin filtering.

Very recently, a tunable δ-potential was doped into the device by the atomic layer doping technique [22], and such a δ-doping was demonstrated to break the intrinsic symmetry. Thus, a structurally controllable spin filter was proposed for spintronics applications [23]. In this work, we assume an SM stripe deposited at the bottom of the semiconductor heterostructure in the device and consider its effect on spin transport for the electron across the device. Theoretical analysis reveals that the inclusion of such an SM stripe also can break the intrinsic symmetry in the device and leads to an obvious spin filtering. Numerical calculations for the InAs material show that the degree of spin filtering depends strongly on the width and/or the position of the SM stripe, which implies that the optimal spin polarization can be achieved by a proper SM stripe. Such a device can serve, therefore, as a spin filter.

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2. Model and theoretical method

Our considered device is described in Fig. 1(a), where an FM stripe with a horizontal magnetization ($\vec{M}_0$) and an SM stripe under an applied negative voltage ($-V_g$) are deposited [24] on the top and at the bottom of the semiconductor heterostructure, and L and d represent the width of the FM and SM stripes, respectively. Fig. 1(b) is the model of the device, where the center of the SM stripe is located at the coordinate x_0. The magnetic profile induced by the magnetized FM stripe can be approximated as [13] two antiparallel δ-function magnetic barriers ($\pm B$) for a small distance between the FM stripe and the 2DEG, and can be usually viewed as homogeneous along the y-direction and varies merely in the x-axis, i.e., $\vec{B} = B_z(x)\hat{z}$ with

$$B_z(x) = BB_0\left[\delta(x+L/2)-\delta(x-L/2)\right], \tag{1}$$

where B is the magnetic field strength with the unit B_0, and L stands for the width of the FM stripe. The corresponding magnetic vector potential can be given, in Landau gauge, by $\vec{A} = [0, A_y(x), 0]$, whose y-component is

$$A_y(x) = B\ell_B\Theta(L/2-|x|), \tag{2}$$

where ℓ_B is the magnetic length and $\Theta(x)$ is the Heaviside step function. Applying a negative voltage to the SM stripe will create an electric potential ($U(x)$) acting on the 2DEG, which can be regarded as [15] a rectangular electric-barrier (U).

The Hamiltonian describing such a 2DEG nanostructure in the (x,y) plane can be written, within the single particle effective mass approximation, as

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

where m^*, m_0, g^* and $\vec{p} = (p_x, p_y)$ are the effective mass, the free mass in vacuum, the effective Landé factor and the momentum of the electron, respectively, and $\sigma = +1/-1$ corresponds to spin-up/spin-down electrons. Using the cyclotron frequency $\omega_c = eB_0/m^*$ and the magnetic length $\ell_B = \sqrt{\hbar/eB_0}$, all the relevant quantities can change to the dimensionless form, e.g., $x\to x\ell_B, B\to BB_0$, and $A_y(x)\to B_0\ell_B A_y(x)$.

Because of the invariant motion of the electron along the y-direction in a magnetic nanostructure, the solution of the stationary Schrödinger equation, $H\Psi(x,y) = E\Psi(x,y)$, has the form $\Psi(x,y) = \psi(x)\exp(ik_y y)$, where k_y is the longitudinal wave-vector, and the wave function in the x-direction, $\psi(x)$, complies with the reduced one-dimensional (1D) Schrödinger equation:

$$\left\{\frac{d^2}{dx^2}+2[E-U_{eff}(x,k_y,U,\sigma)]\right\}\psi(x) = 0, \tag{4}$$

where $U_{eff}(x,k_y,U,\sigma) = [k_y+A_y(x)]^2/2+m^*g^*\sigma B_z(x)/4m_0+U$ is the effective potential for the electron in the device. This effective potential depends on the magnetic profile $B_z(x)$, the longitudinal wave-vector k_y and the spins σ. In fact, it is the dependence of the U_{eff} on the σ that results in the possibility to spin-polarize electrons into the semiconductor material by using this device.

We can solve analytically the 1D Schrödinger equation (4) with the help of the transfer-matrix method [25]. Without any loss of generality, the wave functions in incoming and outgoing regions can be assumed as $\psi_{in}(x) = \exp(ik_l x)+r\exp(-ik_l x)$ for $x<-L/2$ and $\psi_{out}(x) = t\exp(ik_r x)$ for $x>L/2$, respectively, where $k_l = k_r = \sqrt{2E-k_y^2}$ and t/r is the transmission/reflection amplitude. In the device region ($-L/2<x<L/2$), the wave function can be written as the linear combination of the plane waves. By matching these wave functions according to their continuity at the boundaries, we readily obtain the transmission coefficient by means of the transfer-matrix technique as

$$T_\sigma(E,k_y) = \frac{4k_lk_r}{P^2+Q^2}, \tag{5}$$

where $P = k_l m_{11}-\left(\frac{m^*g^*\sigma B}{2m_0}m_{12}+m_{22}\right)k_r$ and $Q = \frac{m^*g^*\sigma B}{2m_0}m_{11}+k_lk_rm_{12}-m_{21}$) with

$$M = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22}\end{pmatrix} = \begin{pmatrix} \cos k_1[x_0+(L-d)/2] & -\frac{\sin k_1[x_0+(L-d)/2]}{k_1} \\ k_1\sin k_1[x_0+(L-d)/2] & \cos k_1[x_0+(L-d)/2]\end{pmatrix}$$
$$\begin{pmatrix} \cos k_2 d & -\frac{\sin k_2 d}{k_2} \\ k_2\sin k_2 d & \cos k_2 d\end{pmatrix}$$
$$\begin{pmatrix} \cos k_3[(L-d)/2-x_0]-\frac{m^*g^*\sigma B}{2m_0k_3}\sin k_3[(L-d)/2-x_0] & -\frac{\sin k_3[(L-d)/2-x_0]}{k_3} \\ k_3\sin k_3[(L-d)/2-x_0]+\frac{m^*g^*\sigma B}{2m_0}\cos k_3[(L-d)/2-x_0] & \cos k_3[(L-d)/2-x_0]\end{pmatrix}. \tag{6}$$

Here, transverse wave-vectors are $k_1 = k_3 = \sqrt{2E-(k_y+B)^2}$ and $k_2 = \sqrt{2(E-U)-(k_y+B)^2}$. Note that, the wave vectors k_l and k_r must be real, but the k_i ($i = 1,2,3$) may be either real or imaginary. When they are imaginary the $\sin(k_i a)$ and $\cos(k_i a)$ change to $\sinh(k_i a)$ and $\cosh(k_i a)$, respectively.

Once the transmission coefficient $T_\sigma(E,k_y)$ is known, the spin polarization of the transmitted electron can be obtained by [7]

$$P_T(E,k_y) = \frac{T_\uparrow(E,k_y)-T_\downarrow(E,k_y)}{T_\uparrow(E,k_y)+T_\downarrow(E,k_y)}, \tag{7}$$

where the $T_\uparrow(E,k_y)$ and $T_\downarrow(E,k_y)$ are the coefficients for spin-up and spin-down electrons, respectively. On the other hand, the spin-electronic ballistic conductance at zero temperature can be calculated by the well-known Landaur–Büttiker formula [26]

$$G_\sigma(E_F) = G_0\int_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} T_\sigma(E_F,\sqrt{2E}\sin\varphi)\cos\varphi\, d\varphi, \tag{8}$$

where φ is the incident angle of the electron with respect to the x-axis, E_F is the Fermi energy, and $G_0 = e^2m^*v_FL_y/h^2$ with the Fermi velocity v_F and the length of the device in the y-direction L_y, respectively. The degree of the electron-spin polarization can be defined by the relative difference or the relative spin conductance excess [13],

$$P_G(E_F) = \frac{G_\uparrow(E_F)-G_\downarrow(E_F)}{G_\uparrow(E_F)+G_\downarrow(E_F)}, \tag{9}$$

where $G_\uparrow(E_F)$ and $G_\downarrow(E_F)$ are conductance for spin-up and spin-down electrons, respectively.

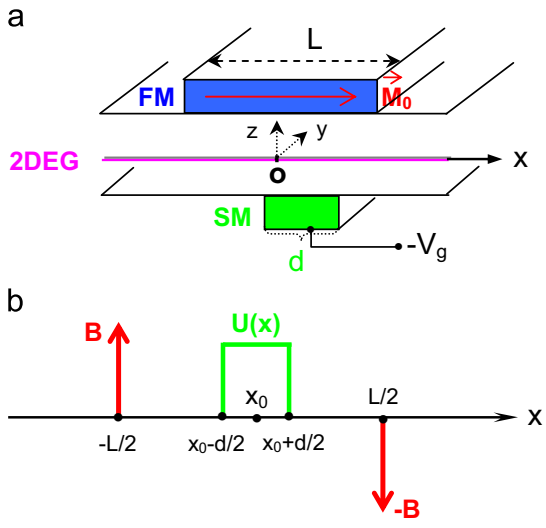

Fig. 1. (Color online) (a) Schematic illustration of the spin filter and (b) its model.