Journal of Magnetism and Magnetic Materials 401 (2016) 231–235

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Spatial spin splitter based on a hybrid ferromagnet, Schottky metal and semiconductor nanostructure

ARTICLE INFO

Keywords:
Hybrid magnetically modulated nanostructure
Lateral displacement
Spin polarization
Spatial spin splitter

ABSTRACT

We theoretically investigate the lateral displacement of the spin electron across a hybrid magnetically modulated nanostructure. Experimentally, this nanostructure can be produced by depositing a ferromagnetic stripe with in-plane magnetization and a Schottky metal stripe on top and bottom of a semiconductor heterostructure, respectively. Theoretical analysis reveals that the inclusion of the Schottky metal stripe in single ferromagnetic-stripe nanostructure can break the intrinsic symmetry and a sizeable spin polarization in the lateral displacement will occur. Numerical calculations demonstrate that both magnitude and sign of the spin polarization can be controlled by adjusting the width and/or the position of the Schottky metal stripe in the device. Thus, based on such a hybrid magnetically modulated nanostructure, a spatial spin splitter can be proposed successfully.

1. Introduction

The use of electron spins to store and process digital information calls for the ability to inject, propagate and manipulate spin with high efficiency [1,2]. Motivated by the field, how to spin-polarize electrons from spatial domain into the conventional semiconductor materials in hybrid magnetically modulated nanostructures (HMMN) [3], where the HMMN is exploited as a spatial spin splitter [4], has attracted much interest in recent years [5–10]. In general, such a scheme spin polarizes electrons into semiconductors by means of significant difference of spatial positions (such as angle, shift and lateral displacement) between spin-up and spin-down electrons across a HMMN [11].

A simple, experimentally attractive proposal [12–14] for spintronic devices is to exploit a single nanosized ferromagnetic (FM) stripe on top of a semiconductor heterostructure. In such a device, the FM stripe with a horizontal magnetization produces an antisymmetric magnetic field, which acts perpendicularly on the two-dimensional electron gas (2DEG) formed usually in a modulation-doped semiconductor heterostructure. Due to this intrinsic symmetry, there is no spin polarization in the single FM-stripe HMMN device [15]. However, in parallel configuration placing a Schottky metal (SM) in the vicinity of the FM stripe can break the intrinsic symmetry, and a spin filter was proposed successfully by Zhai et al. [16]. By adding another FM stripe with an in-plane magnetization on bottom of the semiconductor heterostructure, this intrinsic symmetry also can be broken [17–19]. Therefore, another kind of spin filters also was proposed correspondingly, which may be useful for spintronics applications [20]. Very recently, a tunable δ-potential was introduced into the single FM-stripe device with the help of the atomic layer doping technique or the δ-doping technique [21], and its effect on spin-polarized transport was taken into account. It is found that the δ-doping can break the intrinsic symmetry. As the result of the broken symmetry, such a δ-doped single FM-stripe HMMN device can serve as a structurally controllable spin filter [22] or spatial spin splitter [23].

Edified by the above these brief reports, in the present work, we deposit a SM stripe on the bottom of the semiconductor heterostructure in the single FM-stripe HMMN device, and focus our attention on the influence of the SM stripe on the lateral displacement of the spin electron. Theoretical analysis reveals that the SM stripe will break the intrinsic symmetry, and such a HMMN device can be exploited consequently as a spatial spin splitter for spintronics applications.

2. Model and theoretical method

The HMMN device under consideration is shown in Fig. 1(a), where a FM stripe with a horizontal magnetization ($\vec{M}_0$) and a SM stripe under an applied negative voltage ($-V_g$) are deposited [24] on top and bottom of a semiconductor heterostructure, respectively. The model of this device is presented in Fig. 1(b). The magnetized FM stripe will produce a magnetic field, acting on the 2DEG in (x, y) plane, can be written by [25]

$$\vec{B} = B_z(x)\hat{z},$$
$$B_z(x) = B[\delta(x + L/2) - \delta(x - L/2)], \qquad (1)$$

where B is the magnetic strength of the δ-function magnetic barrier and L stands for the width of the FM stripe. Correspondingly, the magnetic vector potential is given in Landau gauge, by [26,27]

$$\vec{A}(x) = [0, A_y(x), 0]$$
$$A_y(x) = B\Theta(L/2 - |x|), \qquad (2)$$

in which $\Theta(x)$ is the Heaviside step function. The SM stripe applied by a negative voltage also will induce an electric potential $U(x)$, which can be viewed as [12] a rectangular barrier for a small

http://dx.doi.org/10.1016/j.jmmm.2015.10.040
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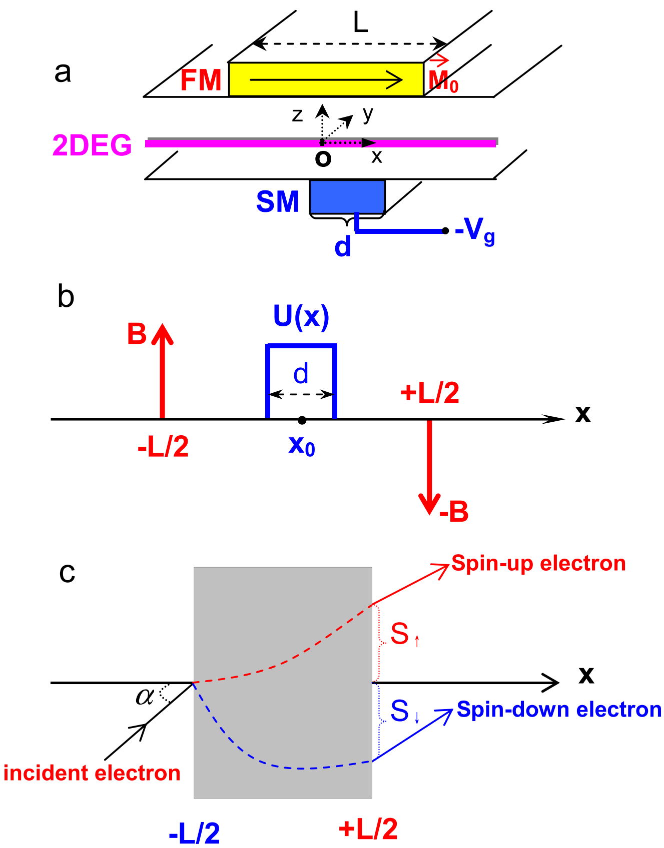

Fig. 1. (a) Schematic illustration of the HMMN device, where a FM stripe with a horizontal magnetization ($\vec{\mathbf{M}}_0$) and a SM stripe under an applied voltage ($-V_g$) are deposited on top and bottom of the semiconductor heterostructure, and L and d are width of the FM and SM stripes, respectively (b) the model of the device, where B is magnetic strength for magnetic profile produced by FM stripe and $U(x)$ is the electric potential induced by SM stripe, and (c) the lateral displacement for the electron tunnelling through this HMMN device.

vertical distance between the SM stripe and the 2EDG with a homogeneous resistivity, i.e.,

$$U(x) = U\Theta(d/2 - |x - x_0|). \tag{3}$$

Here, U is the electric barrier (EB), and the SM stripe with a width d is assumed to locate at x_0. And then, the Hamiltonian describing such a 2DEG system, within the single particle, effective mass approximation, is

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

where m^*, m_0 and e are the effective mass, free mass and charge of an electron, respectively, $\vec{p} = (p_x, p_y)$ is the electronic momentum, g^* is the effective Landé factor of electron, and σ=+1/ − 1 for spin-up/spin-down electrons.

Because of the translational invariance along the y-axis in the HMMN system, the solution of the stationary Schrödinger equation for the electron $H\Psi(x, y) = E\Psi(x, y)$ can be written as $\Psi(x, y) = \psi(x)\exp(ik_y y)$, where k_y is the electronic wave-vector component in y-direction, and the wave function $\psi(x)$ satisfies the following one-dimensional (1D) Schrödinger equation:

$$\{\frac{d^2}{dx^2} + \frac{2m^*}{\hbar^2}\left[E - \frac{eg^*\sigma\hbar}{4m_0}B_z(x) - U(x)\right] - \left[k_y + \frac{e}{\hbar}A_y(x)\right]^2\}\psi(x) = 0, \tag{5}$$

where the quantity $U_{eff}(x) = [\hbar k_y + eA_y(x)]^2/(2m^*) + em^*g^*\sigma\hbar B_z(x)/4m_0 + U(x)$ is referred to as the effective potential of an electron in the HMMN device. Apparently, this effective potential depends on not only the wave vector k_y, magnetic configuration $B_z(x)$ and electron spins σ, but also on the $U(x)$ induced by the SM stripe. In fact, it is this dependence of the $U_{eff}(x)$ on the SM stripe that breaks the intrinsic symmetry in single FM-stripe device and makes such a device serve as a spatial spin splitter.

Obviously, the reduced Schrödinger equation (5) can be analytically solved by linearly combining wave function with plane waves. No loss of generality, the wave function for the electron with the energy E projects onto the HMMN device in an incident angle α [see Fig. 1(c)] can written as $\Psi_{in} = \exp\{i[k_l(x + L/2) + k_y y]\}, x < -L/2$, while the transmitted and reflected wave functions can be expressed in $\Psi_{ref} = \gamma\exp\{i[-k_l(x + L/2) + k_y y]\}, x < -L/2$ and $\Psi_{out} = \tau\exp\{ik_r(x - L/2) + k_y y\}, x > L/2$, respectively, where $k_y = \sqrt{2E}\sin\alpha$, $k_l = k_r = \sqrt{2E - k_y^2}$, and τ/γ is the transmission and reflection amplitudes. By matching wave function at the $\pm L/2$, we can obtain with the help of the transfer matrix method [28,29]

$$\begin{pmatrix} 1 & 1 \\ ik_l & -ik_l \end{pmatrix}\begin{pmatrix} 1 \\ \gamma \end{pmatrix} = M\begin{pmatrix} \tau \\ 0 \end{pmatrix}, \tag{6}$$

with

$$M = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} = \begin{pmatrix} \cos k_1[x_0 + (L-d)/2] & -\frac{\sin k_1[x_0 + (L-d)/2]}{k_1} \\ k_1\sin k_1[x_0 + (L-d)/2] & \cos k_1[x_0 + (L-d)/2] \end{pmatrix} \times \begin{pmatrix} \cos k_2 d & -\frac{\sin k_2 d}{k_2} \\ k_2\sin k_2 d & \cos k_2 d \end{pmatrix} \times \begin{pmatrix} \cos k_3[(L-d)/2 - x_0] - \frac{m^*g^*\sigma B}{2m_0k_3}\sin k_3[(L-d)/2 - x_0] & -\frac{\sin k_3[(L-d)/2 - x_0]}{k_3} \\ k_3\sin k_3[(L-d)/2 - x_0] + \frac{m^*g^*\sigma B}{2m_0}\cos k_3[(L-d)/2 - x_0] & \cos k_3[(L-d)/2 - x_0] \end{pmatrix}. \tag{7}$$

where $k_1 = k_3 = \sqrt{2E - k_y^2}$ and $k_2 = \sqrt{2(E - U) - k_y^2}$. And then, we readily write out

$$\tau = \frac{2k_l}{P + iQ}, \tag{8}$$

where $P = k_l m_{11} + k_r m_{22}$ and $Q = k_l k_r m_{12} - m_{21}$. Therefore, the phase shift for the electron across the HMMN device can be expressed as $\phi = \tan^{-1}(P/Q)$. According to the stationary phase method [5,30,31], the lateral displacement of the spin electron can be calculated by

$$S_\sigma = -\frac{d\phi}{dk_y}. \tag{9}$$

The electron-spin polarization can be defined by considering the relative difference of the lateral displacement [32]

$$P_S = S_\uparrow - S_\downarrow, \tag{10}$$

where $S_\uparrow$ and $S_\downarrow$ are lateral displacements for spin-up and spin-down electrons, respectively.