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Spin spatial splitter based on a magnetic nanostructure with zero average magnetic field

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ABSTRACT

We report a theoretical study on spin-polarized lateral displacement for the electron across a magnetic nanostructure with a zero average magnetic field, which can be experimentally realized by depositing a ferromagnetic stripe with a plumb magnetization on the top of a semiconductor heterostructure. It is shown that, the lateral displacement depends strongly on the electron spins due to the Zeeman coupling and the intrinsic symmetry, though the average magnetic field is vanishing in the nanostructure. It is also shown that the spin-polarized lateral displacement is related closely to the structural parameters. Therefore, such a novel magnetic nanostructure may be used as a spin spatial splitter for spintronics applications.

1. Introduction

It is well-known that, spintronics [1] utilizes the spin of an electron rather than its charge to carry the information, and combines the current semiconductor microelectronic craft to exploit new electronic devices. Comparing with the traditional semiconductor electronic device, this type of electronic devices possesses a lot of excellent performances due to the usage of the spins such as the low power consumption, the large information storage capacity, high data processing speed and dense integration density [2]. The Zeeman coupling mechanism—that is, the external magnetic field interacting with the intrinsic spins, is the most significant among schemes for using the spins of the electron [3]. Therefore, in recent years the magnetic nanostructure—the magnetically modulated semiconductor nanostructure (MMSN) [4] has aroused much attention of both theoretical and experimental researchers working in spintronics applications due to the existence of a god-given good magnetic field.

In particular, very recently the MMSN is used to design the spin spatial splitter [5] for realizing the spin injection into the semiconductor material. In principle, a spin spatial splitter realizes [6] spin polarization by separating electron-spins from the spatial domain, if the spatial position (the angle, shift and displacement) of transmitted electrons out of a semiconductor nanostructure is dependent greatly on the electron-spins. In 2008, Chen et al. [7] first studied the Goos–Hänchen (GH) effect [8] of the electron in a δ-function magnetic-barrier (MB) MMSN, [9] and found simultaneously large and opposite GH displacement between spin-up and spin-down electrons for two δ-MBs in the MMSN pointing at the same direction [10]. Subsequently, the spin-dependent GH shift of the electron in antiparallel double δ-MB MMSN under an applied voltage was investigated by Yuan et al. [11], where two δ-MBs have the unequal magnetic strength [12]. They revealed that the GH shift of spin-up electron is distinct from that of spin-down electron, and consequently a voltage-controllable spin spatial splitter based on this MMSN was proposed successfully. For the realistic MB MMSN, Lu et al. [13] explored the lateral displacement of the transmitted electron, and found that only the MMSN with a symmetric magnetic field profile pertaining to the structural center can be used to the spin spatial splitter. A structurally-controllable spin spatial splitter via the δ-doping technique [14] also were studied by Ma et al. [15] in an antiparallel double δ-MB MMSN. Spin-dependent lateral displacements and corresponding spin spatial splitters were reported one after the other in other MMSNs; cf. partial reference literatures [16–19] as examples.

Motivated by these brief reports, in this paper, we investigate the lateral displacement of the electron through a new MMSN. This MMSN possesses zero average magnetic field, however, the lateral displacement of the transmitted electron is found to be spin-dependent sensitively due to the Zeeman coupling and the intrinsic symmetry. Therefore, such a MMSN can be used as a spin spatial splitter for spintronics applications. Moreover, the degree of spin-polarized lateral displacement is still found to be controllable

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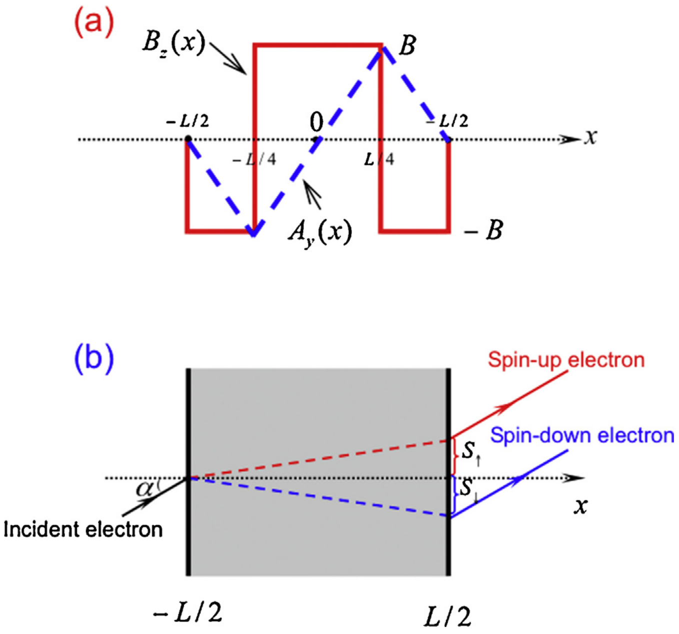

Fig. 1. (a) Schematic illustration of the MMSN, where the solid and dashed curves are the magnetic field profile and the magnetic vector potential, respectively, and (b) the lateral displacement of spin electron across this nanostructure.

by changing the magnetic-field strength and/or the width of the MMSN, which may be helpful for designing an optimal spin spatial splitter.

2. Model and theoretical method

The new MMSN under consideration is a 2EDG modulated by a perpendicular, spatially inhomogeneous magnetic field on the nanometer scale as shown in solid curve of Fig. 1(a), where B and L are the magnetic field strength and the width, respectively. In experiments, such a MMSN can be realized by depositing a nanosized ferromagnetic (FM) stripe with a vertical magnetization on the top of a semiconductor heterostructure [20]. In general, the magnetic field produced by the magnetized FM stripe can be approximately regarded as homogeneous along y-direction and vary only in x direction [21], therefore we have $\vec{B} = B_z(x)\hat{z}$ with

$$B_z(x) = \begin{cases} B, & -L/4 < x < L/4 \\ -B, & -L/2 < x < -L/4 \ \& \ L/4 < x < L/2 \end{cases}. \tag{1}$$

Clearly, this MMSN possesses a zero average magnetic field, i.e., $\langle B_z(x)\rangle$=0. The corresponding magnetic vector potential as presented in dashed curve of Fig. 1(a), can be given, in Landau gauge, by $\vec{A} = [0, A_y(x), 0]$, only with a nonzero y-component

$$A_y(x) = \begin{cases} -B(x+L/2), & -L/2 < x < -L/4 \\ Bx, & -L/4 < x < L/4 \\ -B(x-L/2), & L/4 < x < L/2 \end{cases}. \tag{2}$$

The Hamiltonian describing such a 2DEG nanosystem in the (x, y) plane can be given, within the framework of the single electron, effective mass approximation, by

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

where m^*, m_0, g^* and $\vec{p} = (p_x, p_y)$ are the effective mass, the free mass, the effective Landé g-factor and the momentum of the electron, respectively, σ = +1/−1 stands for spin-up/down case. For convenience, we introduce two characteristic quantities—the cyclotron frequency $\omega_c = eB_0/m^*$ and the magnetic length $\ell_B = \sqrt{\hbar/eB_0}$ with a typical magnetic field B_0, and then all the relevant quantities can be written as dimensionless form, such as $x \to x\,\ell_B$, $B \to BB_0$, $A_y(x) \to B_0\,\ell_B A_y(x)$, $E \to E\,\hbar\,\omega_c \equiv EE_0$, and $\vec{p} \to \vec{p}\hbar/\ell_B$.

Because of the invariant motion of the electron along the y-direction In a MMSN, the solution of the stationary Schrödinger equation, $H\Psi(x, y) = E\Psi(x, y)$, can be expressed as $\Psi(x, y) = \psi(x)\exp(ik_y y)$ with the longitudinal wave vector k_y. While the wave function in the x-direction obeys the following one-dimensional (1D) Schrödinger equation:

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

where $U_{\mathrm{eff}}(x, k_y, \sigma) = [k_y + A_y(x)]^2/2 + m^* g^* \sigma B_z(x)/4m_0$ is usually regarded as the effective potential of the MMSN. Clearly, it depends not only on the magnetic configuration $B_z(x)$ and the longitudinal wave vector k_y, but also on the electron-spin σ via the Zeeman coupling. It is the dependence of the U_{eff} on the σ that leads to the possibility to construct a spin spatial splitter based on this MMSN.

Because the magnetic vector potential $A_y(x)$ has a piecewise linear form in the MMSN region $-L/2 < x < L/2$, Eq. (4) can be exactly solved by virtue of Weber functions [21]. No loss of generality, one can assume the incident, transmitted and reflected wave functions as $\psi_{in}(x) = \exp(ik_l x)$ in $x < -L/2$, $\psi_{out}(x) = t\exp(ik_r x)$ in $x > L/2$ and $\psi_{ref}(x) = r\exp(-ik_l x)$ in $x < -L/2$, respectively, where t/r is transmission/ reflection amplitudes and $k_l = k_r = \sqrt{2E - k_y^2}$. Matching these wave functions in the boundaries: $x = -L/2$, $-L/4$, $L/4$ and $L/2$, one readily obtains $t = 2k_l/z$ with a complex number $z = g\exp(i\varphi)$, and then the phase shift φ of the transmitted electron with respect to the incident electron.

Once the φ is achieved, the spin-dependent lateral displacement for the electron across the MMSN, as sketchily indicated in Fig. 1(b), can be calculated with the help of the stationary phase approximation [7,22,23], by

$$S_\sigma = \frac{d\varphi}{dk_y}. \tag{5}$$

And then, the degree of the spin polarization can be characterized by considering the relative difference of the lateral displacement, i.e. [13],

$$P_S = S_\uparrow - S_\downarrow, \tag{6}$$

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

3. Results and discussion

In the section, we present the results of the spin-dependent lateral displacement for the electron tunneling through the MMSN as shown in Fig. 1(a). For the convenience of the numerical calculation, in the following we assume the semiconductor InAs to be the 2DEG material, i.e., $m^* = 0.024m_0$ and $g^* = 15$, which leads to two basic units $\ell_B = 81.3$ nm and $E_0 = 0.48$ meV for a typical magnetic field $B_0 = 0.1$ T.

To begin with, as the function of the incident energy E we have calculated the lateral displacement S_σ when the spin electron hits onto the MMSN from the left in a given angle of incidence, as is shown in Fig. 2(a). Here, two specific incident angles $\alpha = +85^\circ$ and -85° are taken into account, the structural parameters are taken as $L = 4.0$ and $B = 2.0$, and the solid and dashed curves represent the spin-up and spin-down electrons, respectively. From this figure, one can clearly see that the large lateral displacement is either positive or negative and switches drastically with the incident energy. Also, one can see an antisymmetric behavior of the lateral