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Magnetic control spin-polarization reversal in a hybrid ferromagnet/semiconductor spin filter

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ABSTRACT

Electron spin-polarization reversal is achieved in a hybrid ferromagnet/semiconductor spin filter by introducing the third magnetic barrier and a subtle variation of its strength, and the ground or the second resonance states could be reversed separately by changing its magnetization direction. This interesting feature is believed to be of significant importance for realizing the spin switches and multiple value logic devices.

1. Introduction

Recently spin-related effects in magnetically modulated two-dimensional electron gas (2DEG) have stimulated extensive interests in semiconductor electron spin-filtering devices [1–16]. When depositing ferromagnetic stripes on the top of two-dimensional electron gas (2DEG) heterostructures, the motion of the electrons in the semiconductor could be modulated by the magnetic field provided by the ferromagnetic stripes. Previously, several hybrid ferromagnet/semiconductor spin filtering devices had been proposed, and it had been demonstrated that these kinds of spin filters could reach very high spin-polarization (∼100%), even though the average magnetic field of the structure is zero. Since then, various spin filtering devices of modified configurations have been proposed, and many attractive features had been revealed with the help of numerical calculations [17–19]. It is concluded that the maximum spin splitting could only appear in magnetic structure of anti-symmetry, and no spin splitting could occur in symmetric magnetic structures [20].

As the realization of spintronic devices relies on the ability spin-polarized current generation, injection and detection in semiconductor nanostructures, thus a tunable electron spin-polarization device is most prospects for practical applications. Recently, it is found that the spin polarization and the giant magnetoresistance could be rigorously tuned with an electrostatic potential provided by a normal metal Schottky stripe [21–26]. However, there is no attempt on the magnetic modulation effect on the spin-polarization in a spin filtering diode by a ferromagnetic stripe. Here, we will illustrate the possibility of electron spin polarization magnetic manipulation with a FM stripe of perpendicular magnetization. It is shown that the electron spin-polarization in such a system could be reversed easily by a subtle change of magnetization strength, whether the first or the second resonance state is reversed is simply chose by the magnetization direction of the third middle ferromagnetic stripe. These interesting features are extremely attractive for developing new functional spin filtering devices like the spin switches or and the multiple value logic devices.

2. Model and theoretical calculations

The model spin filter consists of three magnetic-barrier realized by depositing three FM stripes on top/bottom of semiconductor 2DEG. Here, two FM stripes are magnetized parallel to the surface of the 2DEG but opposite to each other, the middle FM stripe is magnetized perpendicular to the surface of the 2DEG, as schematically illustrated in Fig. 1.

The resulting magnetic field for such an arrangement is expressed as

$$\vec{B} = B(x)\vec{z} \tag{1}$$

With

$$B(x) = \begin{cases} B[\delta(x)-\delta(x-d)] & 0 \le x \le d \\ 0 & d \le x \le d+w_1 \\ B_m & d+w_1 \le x \le d+w_1+b/4 \\ -B_m & d+w_1+b/4 \le x \le d+w_1+3b/4 \\ B_m & d+w_1+3b/4 \le x \le d+w_1+b \\ 0 & d+w_1+b \le x \le d+w_1+b+w_2 \\ B[-\delta(x-d-w_1-b-w_2)+\delta(x-2d-w_1-w_2-b) & d+w_1+b+w_2 \le x \le 2d+w_1+b+w_2 \end{cases} \tag{2}$$

here B and B_m are the strength of the magnetic field of each side of the FM strip and the middle FM strip, respectively, d and $b$are the

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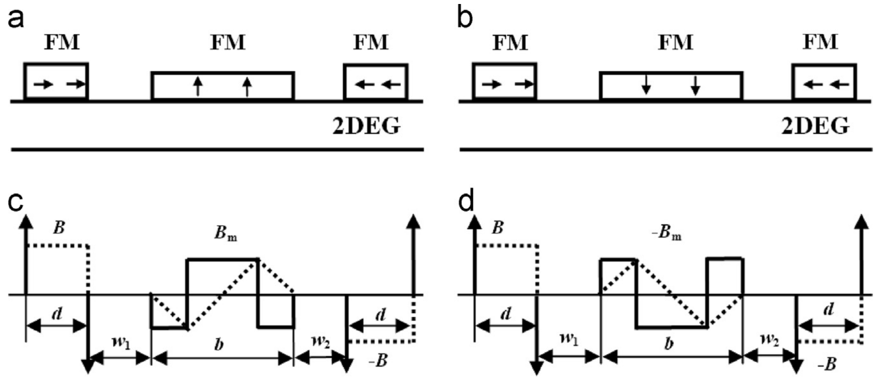

Fig. 1. (a) and (b) show the three FM stripes arrangement, (c) and (d) show the corresponding magnetic field profiles.

width of the left/right barriers and the middle magnetic barrier, respectively, w_1 and w_2 are the distances of the middle magnetic barrier to the left and right magnetic barriers, respectively. The corresponding magnetic vector potential $\vec{A}(x)$ in the Landau gauge is given as

$$A(x)=\begin{cases} B\vec{y} & 0\le x\le d \\ 0 & d\le x\le d+w_1 \\ B_m(x-d-w_1)\vec{y} & d+w_1\le x\le d+w_1+b/4 \\ B_m(-x+d+w_1+b/2)\vec{y} & d+w_1+b/4\le x\le d+w_1+3b/4 \\ B_m(x-d-w_1-b)\vec{y} & d+w_1+3b/4\le x\le d+w_1+b \\ 0 & d+w_1+b\le x\le d+w_1+b+w_2 \\ -B\vec{y} & d+w_1+b+w_2\le x\le 2d+w_1+b+w_2 \end{cases} \tag{3}$$

Depending on the magnetization direction, B_m could be positive or negative, as shown in Fig. 1(a) and (b). In the single electron effective mass approximation, the Hamiltonian describing such a system can be written as

$$H=\frac{1}{2m^*}\left[\vec{P}+e\vec{A}(x)\right]^2+U(x)+\frac{eg^*}{2m_0}\frac{\sigma\hbar}{2}B(x) \tag{4}$$

here m^* is the effective mass of the electron, m_0 is the free electron mass in vacuum, $\vec{P}$ is the momentum of the electron, g^* is the electron effective g-factor in 2DEG, $\sigma=\pm 1$ are for spin up/down electrons.

As the system is translation invariant along the y-direction, the wave vector k_y is a conserved quantity, i.e. $[H, p_y]=0$. Therefore, the wave function can be written as

$$\Psi(x,y)=e^{ik_y y}\psi(x) \tag{5}$$

where k_y is the expectation value of p_y in the y-direction, and the wave function $\psi(x)$ satisfies the one-dimensional (1D) Schrödinger equation

$$\left[\frac{d^2}{dx^2}-\left[\frac{e}{\hbar}A(x)+k_y\right]^2-\frac{m^*g^*\sigma B_z(x)}{2\hbar^2 m_0}+\frac{2m^*E}{\hbar^2}\right]\psi(x)=0 \tag{6}$$

For convenience, we will express all the relevant quantities in dimensionless units. (1) the magnetic field $\vec{B}_z(x)\to B_0\vec{B}_z(x)$; (2) the vector potential $\vec{A}(x)\to B_0 l_B\vec{A}(x)$; (3) the coordinate $\vec{r}\to l_B\vec{r}$; (4) the energy $E\to E_0E$. Here, $E_0=\omega_c$, $\omega_c=eB_0/m^*$ is the electron cyclonic frequency, and $l_B=(/eB_0)^{1/2}$ is the magnetic length with some typical magnetic field B_0.

Now the Schrödinger equation is in the dimensionless form as followed:

$$\left[\frac{d^2}{dx^2}+2E-2V(x,k_y,\sigma)\right]\psi(x)=0 \tag{7}$$

With

$$V(x,k_y,\sigma)=\left[A(x)+k_y\right]^2/2+m^*g^*\sigma B_z(x)/4m_0 \tag{8}$$

The $V(x, k_y, \sigma)$ term is normally interpreted as effective potential; it depends not only on the electron wave vector for motion in the y-direction, but also on the magnetic configuration, as well as on the interaction between the electron spin and the non-homogeneous magnetic field.

By solving the Schrödinger equations and keeping the continuity for both $\psi(x)$ and $\psi'(x)$ at each boundary, we get the following relationships between the reflection amplitude r and transmission amplitude t as:

$$\begin{pmatrix}1\\ r\end{pmatrix}=\frac{1}{2}\begin{pmatrix}1 & -ik^{-1}\\ 1 & ik^{-1}\end{pmatrix}M\begin{pmatrix}1 & 1\\ ik & -ik\end{pmatrix}\begin{pmatrix}t\\ 0\end{pmatrix} \tag{9}$$

$$M=M_L M_{w_1} M_m M_{w_2} M_R \tag{10}$$

$$M_L=\begin{pmatrix}\cos K_L d-\frac{(m^*g^*\sigma B/2m_0)}{K_L}\sin K_L d & -\frac{1}{K_L}\sin K_L d\\ \frac{(m^*g^*\sigma B/2m_0)^2+K_L^2}{K_L}\sin K_L d & \cos K_L d+\frac{(m^*g^*\sigma B/2m_0)}{K_L}\sin K_L d\end{pmatrix}, \tag{11}$$

$$M_R=\begin{pmatrix}\cos K_R d+\frac{(m^*g^*\sigma B/2m_0)}{K_R}\sin K_R d & -\frac{1}{K_R}\sin K_R d\\ \frac{(m^*g^*\sigma B/2m_0)^2+K_R^2}{K_R}\sin K_R d & \cos K_R d-\frac{(m^*g^*\sigma B/2m_0)}{K_R}\sin K_R d\end{pmatrix} \tag{12}$$

$$M_{wj}=\begin{matrix}\cos k_w w_j & -\frac{1}{k_w}\sin k_w w_j\\ k_w\sin k_w w_j & \cos k_w w_j\end{matrix} \tag{13}$$

with $j=1$ or 2. Here M_L, M_R and M_{wj} are the transfer matrices related to the left barrier, the right barrier and the well layers, respectively. $K_L=[2E-(k_y+B)^2]^{1/2}$, $K_R=[2E-(k_y-B)^2]^{1/2}$ and $k_w=[2E-k_y{}^2]^{1/2}$ are the wave vectors in the corresponding regions.

For the middle perpendicular magnetization magnetic barrier, we have

$$M_m=S_-(x_0)S_-^{-1}(x_1)S_+(x_1)S_+^{-1}(x_2)S_-(x_2)S_-^{-1}(x_3) \tag{14}$$

$$S_\pm(x_i)=\begin{bmatrix}\psi_{U_0}(x_i) & \psi_{U_1}(x_i)\\ \frac{d\psi_{U_0}(x_i)}{dx} & \frac{d\psi_{U_1}(x_i)}{dx}\end{bmatrix} \tag{15}$$

The subscript sign $(-)$ and $(+)$ refer to the $-B$ regions or the $+B$ regions, respectively.

With

$$\psi_{U_0}(x)=\exp(-\xi_i^2/2)U_0(\xi_i)$$

$$\psi_{U_1}(x)=\exp(-\xi_i^2/2)U_1(\xi_i) \tag{16}$$