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A bias-tunable electron-spin filter based on a two-dimensional electron gas modulated by ferromagnetic-Schottky metal stripes

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ABSTRACT

We investigate the effect of the bias in an electron-spin filter based on a two-dimensional electron gas modulated by ferromagnetic-Schottky metal stripes. The numerical results show that the electron transmission and the conductance as well as the spin polarization are strongly dependent on the bias applied to the device.

1. Introduction

In the last few years, much attention [1,2] has been paid on the transport of spin-polarized carriers through a near-surface two-dimensional electron gas (2DEG) formed in modulation-doped semiconductor heterostructures [3,4] modulated by ferromagnetic (FM) materials. This interest was motivated by new basic spin properties discovered in these structures and by potential applications in a wide range of spintronic devices such as spin filters [5], spin detectors, and injectors [6,7]. The FM materials provide a magnetic field influencing locally the motion of the electrons in the semiconductor heterostructure. Thus, the electron transmission depends not only on the energy of the incident electrons but also on the direction of their velocity toward the barrier. When both the charge and the spin of the electrons are taken into account, the electronic transport can become spin polarized [8–10].

On the other hand, an important research topic in spintronics is the spin filter which has attracted much attention both theoretically and experimentally [11–14]. This is because that previous efforts depend on spin-injection into a semiconductor from either ferromagnetic metal or magnetic semiconductor, however the efficiency of spin-injection is disappointingly small due to the large conductivity mismatch [15,16]. Therefore, the use of spin filters is an alternative path which can significantly enhance spin injection efficiencies [17,18]. Recently, spin filters based on simple [19–22] and multiple-barrier semiconductor structures [23–28] have been investigated. It was shown that simple barriers exhibit tunneling transmission coefficients dependent on the spin polarization. However, it was also shown that the spin polarization efficiency is relatively low in these structures. Thus, it has been suggested to use multiple-barrier resonant structures to further enhance the device efficiency.

Recently, two electron-spin filters were proposed, one was based on a FM stripe and two Schottky metal (SM) stripes on the 2DEG [29] and the other was based on a SM stipe and two FM stripes on top of the GaAs heterostructure [30], and the large spin polarization is achieved in the two filters. Another electron-spin filter was also proposed by Zhai et al. [31] based on a FM stripe and a SM stripe on the 2DEG. This device can be experimentally realized by placing a SM stripe parallel to the FM stripe on top of the semiconductor heterostructure. It is found that this device possesses a considerable electron-spin polarization effect [32]. Considering such a structure as a single unit and repeating it periodically, spin-polarized transport can be enhanced significantly upon increasing the number of units [33]. In the present work, we further investigate the electron-spin filtering properties in this device under an applied bias. It is shown that the spin polarization of this spin filter strongly depends on the applied bias. This may be helpful for making bias-tunable electron-spin filters.

2. Theoretical method and formulas

The device we consider here is a 2DEG in the (x, y) plane modulated by parallel FM and SM stripes placed on top of the structure, as sketched in Fig. 1(a), which can be realized experimentally by modern nanotechnology [4]. Here, symbols a and c

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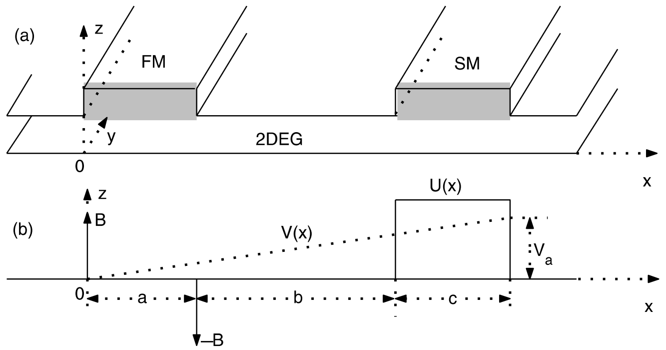

Fig. 1. (a) Schematic illustration of the device. (b) Simplified model exploited in this work.

are the widths of the FM stripe and SM stripe, respectively, and b denotes the spacing between the FM stripe and the SM stripe. If we assume a uniform resistivity within the 2DEG, applying a bias voltage across the 2DEG to induce a triangular electrical potential $V(x)$. The magnetic field $B_z(x)$ provided by the FM stripe and the electrical potential $U(x)$ induced by the SM stripe can be approximated [29] as a delta function and the rectangular electrical barrier, respectively, as shown in Fig. 1(b). We also assume that the magnetic field and the electrical potential are homogeneous in the y direction and vary only along the x axis. The single-particle Hamiltonian describing such a system is

$$H = \frac{[\mathbf{p} + e\mathbf{A}(x)]^2}{2m^*} + \frac{eg^*}{2m_0}\frac{\sigma_z \hbar}{2} B_z(x) + U(x) + \frac{eV_a x}{a+b+c}, \tag{1}$$

where m^* is the effective mass and m_0 the real mass of the electron, $\mathbf{p}$ is the momentum of the electron, $\mathbf{A}(x) = [0, A_y(x), 0]$ is the magnetic vector potential given in the Landau gauge, σ_z represents the z-component of the electron spin ($\sigma_z = +1/-1$ for spin up/down), g^* is the effective Landé factor, and V_a is the bias voltage. For simplicity, we introduce the dimensionless units, the electron cyclonic frequency $\omega_c = eB_0/m^*$ and the magnetic length $l_{B_0} = \sqrt{\hbar/eB_0}$ with B_0 as some typical magnetic field. We will express all the relevant quantities in dimensionless units: (1) the energy $E \to \hbar\omega_c E (= E_0 E)$, (2) the bias voltage $V_a \to \frac{E_0}{e} V_a$, (3) the coordinate $\mathbf{r} \to l_{B_0}\mathbf{r}$, (4) the vector potential $\mathbf{A}(x) \to B_0 l_{B_0}\mathbf{A}(x)$, and (5) the magnetic field $\mathbf{B}_z(x) \to B_0\mathbf{B}_z(x)$. For GaAs ($m^* = 0.067m_0$ and $g^* = 0.44$) and an estimated $B_0 = 0.1$ T, we have $l_{B_0} = 813$ Å and $E_0 = 0.17$ meV. In our calculations, the structure parameters are set to be $B = 3.0$, $U = 4.0$, $b = 0.8$, and $a = c = 0.5$.

Because the system is translation invariant along the y direction, the solution of the stationary Schrödinger equation $H\psi(x, y) = E\psi(x, y)$ can be sought in the form $\psi(x, y) = \exp(ik_y y)\phi(x)$ with k_y the wave vector component in the y direction. The wave function $\phi(x)$ satisfies the one-dimensional (1D) Schrödinger equation $\{\frac{d^2}{dx^2} + 2[E - U_{eff}(x, k_y, \sigma_z, V_a)]\}\phi(x) = 0$. Here, $U_{eff}(x, k_y, \sigma_z, V_a) = \frac{[A_y(x)+k_y]^2}{2} + \frac{m^* g^* \sigma_z B_z(x)}{4m_0} + U(x) + \frac{V_a x}{a+b+c}$ is the effective potential of the corresponding structure. The problem is now reduced to a 1D-tunneling problem. The 1D potential $U(x, k_y, \sigma_z, V_a)$ depends not only on the wave vector k_y, the arrangement of stripes, the interaction between the nonhomogeneous magnetic field and the electron spin σ_z, but also on the bias voltage V_a. Matching the wave functions and their derivatives at all interfaces, the spin-dependent transmission probability through this system $T_{\sigma_z}(E, k_y, V_a)$, can be determined with the transfer matrix method [34]. Thus, the conductance at zero temperature can be calculated from the well-known Landauer–Büttiker formula [35]

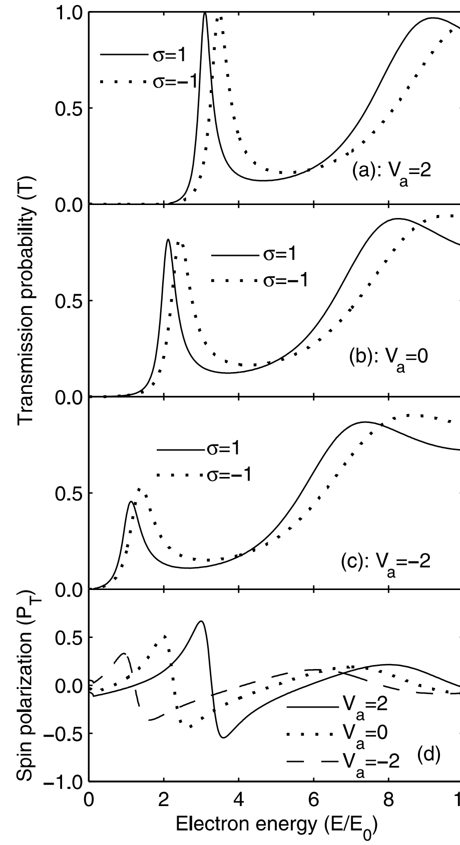

Fig. 2. The transmission probability and the spin polarization P_T for the different biases.

$$G_{\sigma_z}(E_F) = G_0(E_F) \int_{-\pi/2}^{\pi/2} T_{\sigma_z}(E_F, \sqrt{2E_F}\sin\theta, V_a)\cos\theta \, d\theta, \tag{2}$$

where $G_0(E_F) = e^2 m^* \upsilon_F L_y/h^2$, E_F is the Fermi energy, υ_F is the velocity corresponding to E_F, L_y is the length of the barrier structure in the y direction and θ is the angle of incidence relative to the x direction. The electron-spin-polarization effect can be evaluated by calculating the polarization of the transmission probability, defined as $P_T = (T_{+1} - T_{-1})/(T_{+1} + T_{-1})$, or by considering the relative difference between the spin-up and spin-down conductances at the Fermi energy, $P_G = (G_{+1} - G_{-1})/(G_{+1} + G_{-1})$, where T_{+1} and T_{-1} are the transmission probabilities of spin-up and spin-down electrons, respectively, while G_{+1} and G_{-1} are the conductances for spin-up and spin-down electrons, respectively.

3. Numerical results and discussions

First of all, the transmission probability and the spin polarization of transmitted beam under three different biases are shown in Fig. 2 as a function of the electron energy for $k_y = 0.5$. From the figure, it can be apparently seen that with the increase of the bias, the transmission peaks of both spin-up and spin-down electrons significantly shift to the higher energy and become sharper as well as the value of peaks significantly increasing. These features are also clearly reflected in the spin-polarization curves as given in Fig. 2(d). Apparently, with the increase of the bias, the peaks of spin polarization drastically shift rightwards and the value of peaks clearly increases. This can be ascribed to the strong dependence of the effective potential for our considered structure on the applied bias. In addition, the spin polarization rapidly changes its sign and degree with the increase of the electron energy due to