Microelectronics Journal 38 (2007) 401–405

Microelectronics Journal

www.elsevier.com/locate/mejo

Bias-tunable electron–spin polarization in an antiparallel double δ-magnetic-barrier nanostructure

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Received 11 October 2006; accepted 9 January 2007
Available online 12 March 2007

Abstract

We present a theoretical study of spin-dependent electron transport in an antiparallel double δ-magnetic-barrier nanostructure with an applied bias. It is shown that large spin-polarized current can be achieved in such a device with unidentical strength between two δ-magnetic-barriers. It also is shown that the degree of electron–spin polarization is strongly dependent upon the applied bias. These interesting properties may provide an alternative scheme to spin-polarize electrons into semiconductors, and this device may be used as a bias-tunable spin filter.

PACS: 73.40.Gk; 73.23. − b; 72.25. − b; 75.75. + a

Keywords: Spintronics; Spin polarization; Spin filtering; Magnetic quantum structure

1. Introduction

Spintronics is to manipulate the carrier spin to represent digital information [1–3]. This raises the possibility of spin-based semiconductor devices for memory, optoelectronic, and spin–field-effect transistor applications. Spin injection of spin-polarized current into semiconductors is one of the crucial ingredients for a functional spintronic device [4–6]. Previous efforts rely on spin injection into a semiconductor from either ferromagnetic metal or magnetic semiconductor [7,8]. However, an efficiency of spin injection through ideal ferromagnetic/semiconductor interface is disappointingly small due to the large conductivity mismatch [9–11], and Curie temperature is low when magnetic semiconductors are used as the spin injector [7,8]. The use of spin filters is, therefore, an alternative approach, which can significantly enhance spin injection efficiencies [12].

Recent studies [13–15] indicated that spin polarization of current can also be achieved by passing it across a two-dimensional electron gas (2DEG) plane, under the influence of spatially nonuniform, perpendicular-to-plane, magnetic barriers. Such a type of system is the hybrid of semiconductors and magnetic materials, where a ferromagnetic material is deposited on top of a near-surface 2DEG formed in modulation-doped semiconductor heterostructure. The magnetic materials provide a magnetic field which can influence locally the motion of the electrons in the semiconductor heterostructure. A simple, experimentally attractive proposal for spintronic devices was to exploit a single ferromagnetic (FM) stripe on top of a 2DEG [13,16]. This device has been discussed widely, and many interesting results were obtained via numerical calculation. Nevertheless, recent computations have shown that there is no spin polarization and spin filtering in a pure magnetic barrier or a hybrid magnetic-electric barrier with double antiparallel δ-function magnetic fields [16–18].

Very recently, it is shown that [19] such a device possesses the considerable spin polarization if two δ-magnetic-barriers have unidentical magnetic strengths. A tunable spin-polarized source is desirable for spintronic applications [20]. In order to manipulate spin polarization, in this paper we consider spin-dependent tunneling through such a device under an applied bias. By numerical

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0026-2692/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.mejo.2007.01.014

calculations for realistic InAs material system, we demonstrate that not only the amplitude of the polarization but also its sign varies with the bias, thus the considered device can be employed as a bias-controllable spin filter.

2. Model and method

The system under consideration is a magnetically modulated 2DEG formed usually in a modulation-doped semiconductor heterostructure, which can be experimentally realized [21] by depositing two metallic FM stripes on the top and bottom of a semiconductor heterostructure, as schematically depicted in Fig. 1(a). The in-plane magnetization of the FM layers creates an out-of-plane fringe magnetic field at both ends. This fringe field constitutes a nonhomogeneous magnetic barrier for electron transport within the 2EDG. The two FM stripes are asymmetric in length with a distance between their right edges. They are also different in distance relative to the 2DEG (the distance of the upper FM layer is smaller than that of the FM layer at the bottom), which will result in the magnetic barriers produced by the two FM layers with unidentical strengths. Making use of the modern nanotechnology such a system can be deliberately designed to fall short of the left-hand edge of the FM layers, so that the effects of fringe field there can be ignored. Applying a bias voltage across the 2DEG induces a triangular electrical potential, if we assume a uniform resistivity within the 2DEG. For simplicity, the magnetic barrier is approximated [16] as a delta function (solid curve) together with the triangular electrical barrier (dashed curve) shown in Fig. 1(b). The magnetic field can be expressed as

$$\mathbf{B} = B_z(x)\hat{z},$$

$$B_z(x) = [B_1\delta(x + L/2) - B_2\delta(x - L/2)], \tag{1}$$

where B_1 and B_2 are the magnetic strengths of two δ-function barriers, and L is their separation. Assume that the magnetic field provided by the FM stripe, $B_z(x)$, and the electrical potential induced by the applied bias, $U(x)$, are homogeneous in the y direction and varies only along the x-axis. The motion of an electron in such a modulated 2DEG system in the (x, y) plane, can be described by the single-particle Hamiltonian,

$$H = \frac{p_x^2}{2m_e^*} + \frac{[p_y^2 + (e/c)A_y(x)]^2}{2m_e^*} + \frac{eg^*}{2m_e}\frac{\sigma_z\hbar}{2c}B_z(x) - \frac{eV_\alpha}{L}x, \tag{2}$$

where m_e^* is the effective mass, and m_e is the free electron mass, (p_x, p_y) is the electron momentum, and g^* is the effective Lande factor of the electron in the 2DEG. $\sigma_z = +1/-1$ for spin-up/down electrons, and the magnetic vector potential of the device can be written as $\mathbf{A} = [0, A_y(x), 0]$ in the Landau gauge, i.e.,

$$A_y(x) = \begin{cases} 0, & x < -L/2, \\ B_1, & -L/2 < x < +L/2, \\ B_1 - B_2, & x > L/2, \end{cases} \tag{3}$$

which results in $B_z(x) = \mathrm{d}A_y(x)/\mathrm{d}x$. Because of the translational invariance of the system along the y direction, the total electronic wave function can be written as $\Phi(x, y) = \mathrm{e}^{\mathrm{i}k_y y}\psi(x)$, where k_y is the wave vector component in the y direction. Accordingly, the wave function $\psi(x)$ satisfies the following reduced one-dimensional (1D) Schrodinger equation:

$$\left\{\frac{\hbar^2}{2m_e^*}\frac{\mathrm{d}^2}{\mathrm{d}x^2} - \left[\frac{\hbar k_y + eA_y(x)}{2m_e^*}\right]^2 + \left[E + \frac{eV_\alpha}{L}x - \frac{eg^*\sigma_z\hbar}{4m_e}B_z(x)\right]\right\}\psi(x) = 0, \tag{4}$$

where $U_{\mathrm{eff}}(x, k_y, V_\alpha, \sigma_z) = [\hbar k_y + eA_y(x)]^2/(2m_e^*) + eg^*\sigma_z\hbar B_z(x)/(4m_e) - (eV_\alpha/L)x$ is usually called as the effective electric potential of the corresponding system. Clearly, it depends not only on the magnetic configuration $B_z(x)$ of the system, the transverse wave vector k_y of the electron, and the electronic spin σ_z, but also on the bias V_α.

The reduced 1D Schrodinger equation can be solved by using the transfer-matrix method [15]. In the left and right regions of the nanosystem, the wave functions are $\psi_{\mathrm{left}}(x) = \exp(\mathrm{i}k_{\mathrm{left}}x) + \gamma\exp(-\mathrm{i}k_{\mathrm{left}}x)$, $x < x_-$ and $\psi_{\mathrm{right}}(x) = \tau\exp(\mathrm{i}k_{\mathrm{right}}x)$, $x > x_+$, where $k_{\mathrm{left}} = \sqrt{2m_e^*E - [eA_{y(\mathrm{left})}(x) + \hbar k_y]^2}/\hbar$, $k_{\mathrm{right}} = \sqrt{2m_e^*E - [eA_{y(\mathrm{right})}(x) + \hbar k_y]^2}/\hbar$, and γ/τ is the reflection/transmission amplitude. Following Ref. [15], one can obtain the V_α-dependent transmission probability for incident electron with energy E, wave vector k_y, and spin orientation σ_z by

$$T(E, k_y, \sigma_z, V_\alpha) = \frac{k_{\mathrm{right}}}{k_{\mathrm{left}}}|\tau|^2. \tag{5}$$

Once the spin-dependent transmission is obtained, one can see to what extent their structure is reflected in measurable quantities, which involves some kinds of

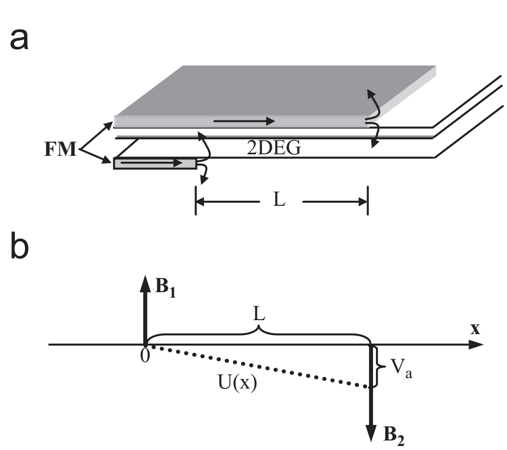

Fig. 1. (a) Schematic overview of the device and (b) the model magnetic field and the model triangular electric potential used in the calculation.