Spin-dependent transport for a two-dimensional electron gas with magnetic barriers*

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(Received 23 May 2009; revised manuscript received 10 September 2009)

The spin-dependent conductance and magnetoresistance ratio (MRR) for a semiconductor heterostructures consisting of two magnetic barriers with different height and space have been investigated by the transfer-matrix method. It is shown that the splitting of the conductance for parallel and antiparallel magnetization configurations results in tremendous spin-dependent MRR, and the maximal MRRs reach 5300% and 3800% for the magnetic barrier spaces $W = 81.3$ and 243.9 nm, respectively. The obtained spin-filtering transport property of nanostructures with magnetic barriers may be useful to magnetic-barrier-based spintronics.

Keywords: semiconductor 2DEG, magnetic barriers, spin-dependent transport
PACC: 7320D, 7335A, 7570P

The electronic transport properties in magnetically modulated semiconductor heterostructures have been attracting considerable attention since the discovery of the giant magnetoresistance (GMR) effect.[1] In the presence of the magnetic-barrier tunneling structure, which can be realized experimentally[2] by depositing ferromagnetic conducting or superconducting stripes on the surface of a semiconductor heterojunction two-dimensional electron gas (2DEG), the electron transport in various cases has been investigated.[3−6] The studies of antiparallel magnetic–electric barriers[7] and tilted magnetic field[8] in a 2DEG revealed resonant tunneling and wave vector filtering properties. The GMR effect of 2DEG with periodically modulated magnetic field[9] and magnetic-electric barrier[10] has been demonstrated, other than the negative GMR effect in inhomogeneous semiconductors.[11] Meanwhile, magnetoresistance in magnetic tunneling junctions was found to be essentially dependent on the height, width, and effective electron mass of the potential barrier but for the bias voltage. Furthermore, the spin polarization effect[12−14] was proposed to be related to the magnetic configuration, the applied bias and the incident electron energy. In addition to an efficient way to control spin polarization by the external electric field[15] and magnetic barriers,[16] the bias voltage was also used to manipulate the spin polarization by Honda *et al.*[17] The above results have been proposed to be used in designing spin memory devices and spin transistors.[18] However, for the conductance and MRR there lack investigations which take into consideration the spin influence on the 2DEG modulated by magnetic barriers.[19]

We note that previous works[9,10] have omitted the Zeeman term of the Hamiltonian in numerical calculations because of its comparatively small value which results in spin-independent transport properties in the system. In this work, we present a theoretical investigation on the influence of the intrinsic electron spin on the conductance and MRR for a 2DEG modulated by two different magnetic barriers. The conductance splitting and the spin-up and spin-down electronic MRR for the 2DEG under both parallel (P) and antiparallel (AP) alignments have been demonstrated by means of the transfer-matrix method and the Landauer–Büttiker theory. Owing to the interaction between spin and magnetic field, the splitting becomes weak with the increase of the space between the magnetic barriers. The results are discussed and compared with those in related previous works.[9,10,19] The spin-filtering property found here is expected to

*Project supported by the National Natural Science Foundation of China (Grant Nos. 10574042 and 10974052), the Specialized Research Fund for the Doctoral Program of Higher Education of China (Grant No. 20060542002).
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be useful in the design of spin-dependent devices.

In the effective-mass approximation, the Hamiltonian of a magnetic Kronig–Penney superlattice[9,10,19−21] 2DEG modulated by a perpendicular magnetic field $B_z(x) = B_0\gamma_1\ [\delta(x-81.3)-\delta(x-162.6)]+\lambda B_0\gamma_2\ [\delta(x-162.6-W)-\delta(x-L)]$ with $B_0\gamma_1$ and $B_0\gamma_2$ being the magnetic field strengths of the two magnetic barriers, W the space between them, $L = W+243.9$ nm the length of a period and $\lambda = 1/-1$ for P/AP alignment of the magnetization configuration, is

$$H = \frac{1}{2m^*}[\boldsymbol{p} + e\boldsymbol{A}(x)]^2 + \frac{e\hbar g^*}{4m^*}\sigma_z B_z(x), \qquad (1)$$

where m^* is the effective mass of an electron, e the absolute value of the electron's charge, $\boldsymbol{p}$ the momentum operator, g^* the effective Landé factor of the electron in the semiconductor heterojunction 2DEG and $\sigma_z = +1/-1$ for spin-up/spin-down electrons. The system described by the above Hamiltonian is translational invariant along the y direction, therefore, the total wave function can be expressed as $\Psi(x,y) = \mathrm{e}^{\mathrm{i}\,k_y y}\Phi(x)$ with k_y the Bloch wave vector in the y direction. All the physical quantities can be expressed in dimensionless units by introducing the cyclotron frequency $\omega_c = eB_0/m^*$ and the magnetic length $l_B = \sqrt{\hbar/eB_0}$, such as, the magnetic field $B_z(x) \to B_z(x)B_0$, the coordinate $\boldsymbol{r} \to \boldsymbol{r}l_B$, the vector potential $\boldsymbol{A}(x) \to \boldsymbol{A}(x)B_0 l_B$ and the energy $E \to E\hbar\omega_c$. For $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$/GaAs semiconductor $g^* = 0.44$, m^* is taken to be 0.067 m_e (m_e is the free electron mass), hence $l_B = 81.3$ nm and $E_0 = \hbar\omega_c = 0.17$ meV under the condition of $B_0 = 0.1$ T.

Substituting $\Psi(x,y) = \mathrm{e}^{\mathrm{i}\,k_y y}\Phi(x)$ into the Schrödinger equation for Hamiltonian (1) with dimensionless quantities, one obtains a one-dimensional equation

$$\left\{\frac{\mathrm{d}^2}{\mathrm{d}x^2} - [k_y + A(x)]^2 - g^*\sigma_z B_z(x)/2 + 2E\right\}\Phi(x) = 0. \qquad (2)$$

Defining $K^2 = 2E - [k_y + A(x)]^2 - g^*\sigma_z B_z(x)/2$, then Eq. (2) reduces to $[\mathrm{d}^2/\mathrm{d}x^2 + K^2]\Phi(x)=0$. When the magnetic modulation is restricted to the region of $0 \le x \le L$, which is divided into N segments of width $d = L/N$ ($N \gg 1$), the vector potential $A(x)$ is zero at $x < 0$ and $x > L$, while $A(x_j)$ in the jth segment of $x \in [jd,(j+1)d]$ is assumed to be a constant. Therefore, the wave function $\Phi(x)$ can be expressed as

$$\Phi(x) = \begin{cases} c_l\mathrm{e}^{\mathrm{i}\,K_l x} + d_l\mathrm{e}^{-\mathrm{i}\,K_l x}, & (x<0), \\ c_j\mathrm{e}^{\mathrm{i}\,K_j(x-jd)} + d_j\mathrm{e}^{-\mathrm{i}\,K_j(x-jd)}, (j=1,2,\ldots,N), & (0\le x\le L), \\ c_r\mathrm{e}^{\mathrm{i}\,K_r(x-L)} + d_r\mathrm{e}^{-\mathrm{i}\,K_r(x-L)}, & (x>L), \end{cases} \qquad (3)$$

where $K_l = K_r = \sqrt{2E - k_y^2}$, $K_j = \sqrt{2E - [k_y + A(x_j)]^2 - g^*\sigma_z B_z(x)/2}$ with $x_j = jd$, and c_α and d_α ($\alpha = l$, r, j) are the wave function coefficients.

According to the continuity of wave functions and their derivations at $x = 0$, $(j+1)d$ and L, one obtains

$$\begin{aligned}\begin{bmatrix} c_r + d_r \\ c_r - d_r \end{bmatrix} = &\begin{bmatrix} \cos(K_N d) & \mathrm{i}\sin(K_N d) \\ \mathrm{i}(K_N/K_r)\sin(K_N d) & (K_N/K_r)\cos(K_N d) \end{bmatrix} \prod_{j=1}^{N-1} M(j) \\ &\times \begin{bmatrix} \cos(K_l d) & \mathrm{i}\sin(K_l d) \\ \mathrm{i}(K_l/K_1)\sin(K_l d) & (K_l/K_1)\cos(K_l d) \end{bmatrix} \begin{bmatrix} c_l + d_l \\ c_l - d_l \end{bmatrix}, \end{aligned} \qquad (4)$$

where

$$M(j) = \begin{bmatrix} \cos(K_j d) & \mathrm{i}\sin(K_j d) \\ \mathrm{i}(K_j/K_{j+1})\sin(K_j d) & (K_j/K_{j+1})\cos(K_j d) \end{bmatrix} \qquad (5)$$

is the transfer-matrix. Equation (4) can be reduced to a simpler form

$$\begin{bmatrix} c_r + d_r \\ c_r - d_r \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \begin{bmatrix} c_l + d_l \\ c_l - d_l \end{bmatrix}, \qquad (6)$$

where m_{ij} (i,j=1,2) are the matrix elements of the successive multiplication of N+1 matrices on the right hand side of Eq. (4). On the right hand side of the potential barrier, there exist only transmission waves, i.e., $d_r = 0$. Therefore, the spin-dependent transmission probability through the barriers can be obtained from Eq. (6)

$$T_\sigma(E_F, k_y) = 1 - \left|\frac{d_l}{c_l}\right|^2 = 1 - \left|\frac{m_{11} + m_{12} - m_{21} - m_{22}}{m_{12} + m_{21} - m_{11} - m_{22}}\right|^2. \tag{7}$$

Consequently, the spin-dependent ballistic conductance can be calculated from the Landauer–Büttiker formula[22]

$$G_\sigma = G_0 \int_{-\pi/2}^{\pi/2} T_\sigma(E_{\rm F}, \sqrt{2E_{\rm F}}\sin\theta)\cos\theta {\rm d}\theta, \tag{8}$$

where $G_0 = 2e^2 m^* v_{\rm F} l_y/\hbar^2$ with $v_{\rm F}$ being the Fermi velocity, l_y the length of the structure in the y direction, $E_{\rm F}$ is the Fermi energy and θ the angle between the incident direction and the x-axis. Moreover, the spin-dependent MRR is defined[23] as ${\rm MRR}_\sigma = (G_{\sigma{\rm P}} - G_{\sigma{\rm AP}})/G_{\sigma{\rm AP}}$ with $G_{\sigma{\rm P}}$ and $G_{\sigma{\rm AP}}$ being the conductances for the parallel and antiparallel alignments, respectively.

Next, we present some numerical examples of the spin-dependent conductance G_σ and MRR calculated for an $Al_xGa_{1-x}As$/GaAs 2DEG modulated by two magnetic barriers with different strengths of $B_0\gamma_1 = 0.1$ T and $B_0\gamma_2 = 0.5$ T. The spin-dependent conductance (in units of G_0) as a function of Fermi energy $E_{\rm F}$ (in units of E_0) under the parallel configuration is shown in Figs. 1(a) for the space $W = 81.3$ nm and 2(a) for $W = 243.9$ nm. As shown by the thick (for spin-up) and thin (for spin-down) solid lines in Fig. 1(a), the two lines increase alternatively with the increase of Fermi energy, the spin-up conductance is smaller than that of spin-down in the range of $3.9 < E_{\rm F} < 5.5$ while it is larger in the range of $5.5 < E_{\rm F} < 7.0$, and the conductances for both spin-up and spin-down are nearly zero within the energy range of $0 < E_{\rm F} < 2.8$. However, a more frequent alternative structure is demonstrated by the two corresponding lines in Fig. 2(a) when the barrier space W increases up to 243.9 nm. This result is consistent with Figs. 2 and 4 of Ref. [19] in which spin effect was included. Furthermore, Figs. 1(b) and 2(b) present the spin-dependent conductance versus the Fermi energy under the antiparallel alignment for the magnetic barrier spaces $W = 81.3$ and 243.9 nm, respectively. As shown by the thick and thin solid lines in Fig. 1(b), the two lines also increase alternatively with the Fermi energy and the spin-up conductance is smaller than that of spin-down in the range of $3.9 < E_{\rm F} < 5.5$ while it is larger in the range of $5.5 < E_{\rm F} < 7.0$. Both the spin-up and spin-down conductances are nearly zero in the energy range of $0 < E_{\rm F} < 3.5$ due to a much stronger suppression in the case of the antiparallel configuration. Moreover, a more frequent alternation is demonstrated in Fig. 2(b) (for $W = 243.9$ nm), which also agrees with the results of Ref. [19]. We owe the large MRR in Figs. 1(c) and 2(c) to the finite conductance for parallel barrier configuration and

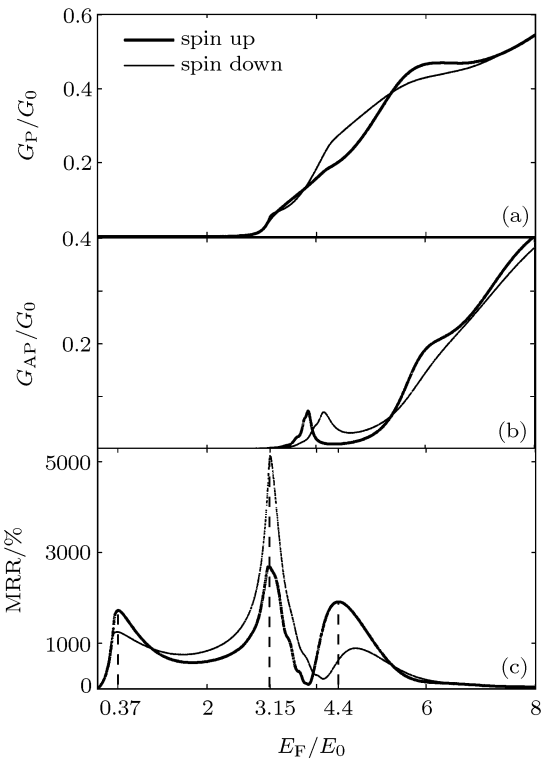


Fig. 1. Conductances for (a) parallel, (b) antiparallel alignment configuration, and (c) the magnetoresistance ratio as functions of Fermi energy. The magnetic-barrier structure parameters are $W = 81.3$ nm and $L = 325.2$ nm while the two magnetic strengths are 0.1 and 0.5 T. The thick and thin solid lines correspond to spin-up and spin-down, respectively.

nearly zero conductance for antiparallel barrier configuration in the energy ranges of $2.8 < E_{\rm F} < 3.5$ and $2.8 < E_{\rm F} < 4.3$. The nearly zero spin-dependent conductance for these energies may come from bound state effects in the system modulated by magnetic barriers. Therefore, the stronger evanescence effect for antiparallel than for parallel magnetic configuration results in large MRR at some energies. The more frequent oscillations for the wider space case in Figs. 2(a) and 2(b) as compared with Figs. 1(a) and 1(b) will also be demonstrated in MRR for the system as follows.

The MRRs for the system as a function of the Fermi energy for spaces $W = 81.3$ and 243.9 nm are shown in Figs. 1(c) and 2(c), respectively. As illustrated by the thick and thin solid lines in Fig.1(c) respectively for the spin-up and spin-down MRR (in the peak regime the solid lines almost become dashed due to the step-limitation in numerical integration), both lines present a highest peak value at $E_{\rm F} = 3.15$ other than the asymmetrically distributed lower peaks in the vicinity of 0.37 and 4.4. However, the maximal MRR for spin-down (about 5300%) is much larger than that (2500%) for spin-up. Moreover, Fig. 2(c) demonstrates the MRR in the case of the space $W =$ 243.9 nm. In addition to the fast-oscillated (appears black because of the resolution) increase of MRR in the range of $1.0 < E_{\rm F} < 2.8$, one notes maximal MRRs with the heights of 3800% and 2800% respectively for spin-up and spin-down at $E_{\rm F} = 4.2$. Besides, the MRR peaks at $E_{\rm F} = 3.15$ are lower than those in the narrower space case while the peaks at $E_{\rm F} = 4.2$ are higher and sharper than the ones near $E_{\rm F} = 4.4$ in Fig. 1(c). It should be pointed out that the system MRRs would decrease and oscillate strongly as the space increases, which can be physically comprehended similarly to those in Fig. 2 of Ref. [10]. Therefore, one may obtain the expected spin-dependent conductances and MRRs by choosing appropriate spaces between the magnetic barriers and incident energies, which may be used to manipulate the spin-dependent electronic transport properties. One notes that the splitting of the spin-dependent conductance and MRR is not large enough owing to the small Zeeman coupling and magnetic barrier space, and all the results presented here are obtained at zero temperature. Considering the influence of finite temperature,[9,10] the electron mean free path will decrease and the ballistic conductance should mainly come from electrons with energies within $(E_{\rm F} - k_{\rm B}T,\ E_{\rm F} + k_{\rm B}T)$, and the magnetoresistance should increase accordingly.

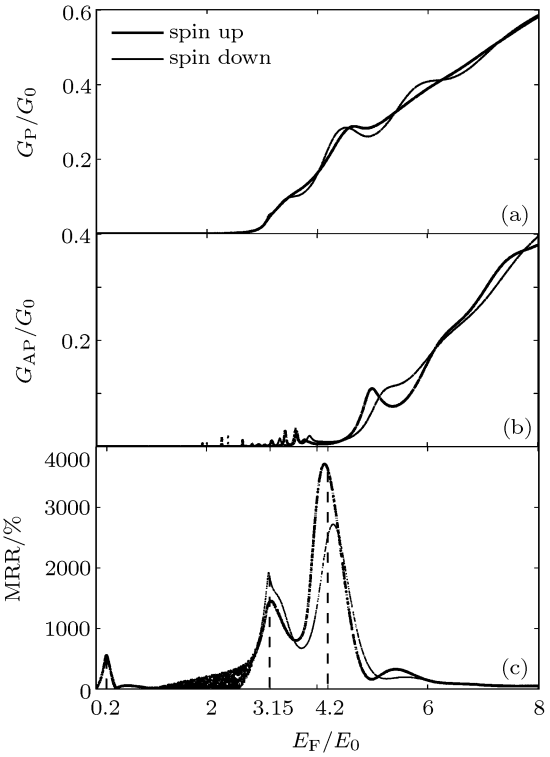


Fig. 2. The conductances for (a) parallel, (b) antiparallel alignment configurations and (c) the magnetoresistance ratio as functions of the Fermi energy. All other parameters are the same as in Fig. 1 but with different magnetic-barrier structure parameters of $W = 243.9$ nm and $L = 569.1$ nm.

In conclusion, the effect of spin on the ballistic conductance and MRR in a 2DEG modulated by two different magnetic barriers have been investigated by the transfer-matrix method and Landauer–Büttiker formula. The splitting of the spin-dependent conductance for parallel and antiparallel magnetization alignments results in a tremendous spin-dependent magnetoresistance effect. The obtained spin-filtering property of magnetic barrier modulated nanostructures may be useful in designing magnetic-barrier-based spintronic devices.

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