# Effects of intrinsic spin on electronic transport through magnetic barriers

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It is shown that the interaction of the intrinsic spin of two-dimensional electrons with the magnetic field significantly changes the tunneling probability of electrons through magnetic barriers and the conductance of devices having such barriers with respect to the case where this interaction is neglected. It is also shown that certain structures having these magnetic barriers possess the ability to distinguish the two possible spin states of the electrons. [S0163-1829(96)04442-6]

The electronic-transport properties of semiconductor heterostructures in the presence of inhomogeneous magnetic fields on the nanometer scale have been recently studied. Such magnetic fields have been experimentally created by the fabrication of magnetic dots[1] and lithographic patterning of ferromagnetic materials[2] and type-II superconductors[3] on conventional semiconductor heterostructures. Theoretically, the motion of an electron in various types of magnetic fields have been studied.[4]

New tunneling structures consisting of magnetic barriers for two-dimensional electron gas (2DEG) have been proposed theoretically[5] where the form of the equivalent potential for the 2DEG depends on the wave vector of the incident electron. The tunneling probability and the conductance of a resonant tunneling device consisting of such magnetic barriers exhibits pronounced resonances with the electronic energy. However, in these works, the effect of the intrinsic spin of the electron on the effective potential was not considered.

The aim of this paper is to highlight the effect of the interaction of the intrinsic electronic spin with the magnetic field. It is shown that the tunneling probability and the conductance are altered due to this interaction and that certain structures having these magnetic barriers possess the ability to distinguish the two possible spin states of an electron.

For the analysis, we consider a 2DEG in the $xy$ plane with a magnetic field in the $z$ direction. We take a simple $\delta$-function magnetic field of the form $\mathbf{B}=B_z(x)\hat{z}$ with $B_z(x)=B_0\lambda[\delta(x+d/2)-\delta(x-d/2)]$, where $B_0\lambda$ gives the strength of the magnetic field and $d$ is the separation between the two $\delta$ functions. This form of the magnetic field is an approximation to the field that can be realized with ferromagnetic stripes[5] and is useful because it permits the calculation of the transmission probability in closed form.

A 2DEG in the $xy$ plane with a magnetic field pointing in the $z$ direction is described by the Hamiltonian

$$\mathcal{H}=\frac{1}{2m^*}[\mathbf{p}+e\mathbf{A}(x)]^2+\frac{eg^*}{2m^*}\frac{\sigma\hbar}{2}B_z(x), \tag{1}$$

where $m^*$ is the effective mass of the electron, $\mathbf{p}$ is the momentum of the electron, $g^*$ is the effective $g$ factor of the electron in a real 2DEG realized using semiconductors, $\sigma=+1/-1$ for up/down spin electrons, and $\mathbf{A}(x)$ is the magnetic vector potential given, in the Landau gauge, by $\mathbf{A}(x)=B_0\lambda\hat{y}$ for $-d/2<x<d/2$ and zero otherwise. We introduce dimensionless units for the simplicity in expressing the results. For that we need the cyclotron frequency $\omega_c=eB_0/m^*$ and the magnetic length $l_B=\sqrt{\hbar/eB_0}$. The relevant quantities are expressed in dimensionless units: (1) the magnetic field $B(x)\rightarrow B_0B(x)$, (2) the vector potential $A(x)\rightarrow B_0l_BA(x)$, (3) the coordinate $x\rightarrow l_Bx$, and (4) the energy $E\rightarrow\hbar\omega_cE$.

The two-dimensional Schrödinger equation $\mathcal{H}\Psi(x,y)=E\Psi(x,y)$ with $\mathcal{H}$ given by Eq. (1) in the dimensionless units has solutions of the form $\Psi(x,y)=e^{iqy}\psi(x)$, where $E$ is the total energy of the electron and $q$ is the electron wave vector in the $y$ direction. The wave function $\psi(x)$ satisfies the one-dimensional Schrödinger equation with an effective potential $V(x)=[A(x)+q]^2/2+g^*\sigma B_z(x)/2$. The last term in the effective potential is zero everywhere except at $x=\pm d/2$. It only introduces a discontinuity in the first derivative of the wave function at those coordinates. The transmission probability, $T(E,q)$, is evaluated by the standard procedure outlined in quantum mechanics texts and is given by

$$T(E,q)=\begin{cases}\dfrac{4k_1^2k_2^2}{[2k_1k_2\cos(k_2d)+2\sigma\lambda^*k_1\sin(k_2d)]^2+\{-2\sigma\lambda^*k_2\cos(k_2d)+[k_1^2+k_2^2-(\sigma\lambda^*)^2]\sin(k_2d)\}^2}, & 2E>(q+\lambda^*)^2\\[2ex] \dfrac{4k_1^2k_2^2}{[2k_1k_2\cosh(k_2d)+2\sigma\lambda^*k_1\sinh(k_2d)]^2+\{-2\sigma\lambda^*k_2\cosh(k_2d)+[k_1^2-k_2^2-(\sigma\lambda^*)^2]\sinh(k_2d)\}^2}, & 2E<(q+\lambda^*)^2,\end{cases} \tag{2}$$

 

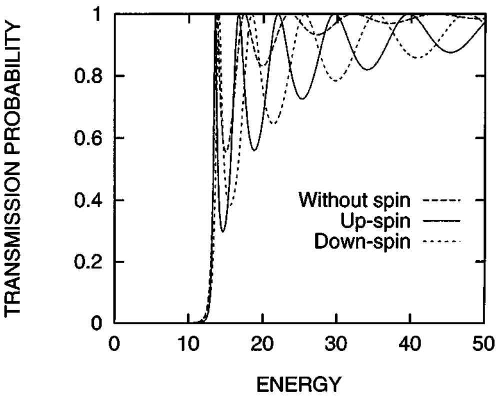


FIG. 1. Energy dependence of the transmission probability of an electron with $q=2$ and $g^*=0.44$ through the magnetic barrier structure with $\lambda=14$ and $d=2$.

where $k_1=\sqrt{2E-q^2}, k_2=\sqrt{|2E-(q+\lambda^*)^2|}$ and $\lambda^*=g^*\lambda/2$. For $E<q^2/2, T(E,q)=0$. We plot the transmission probability as a function of the energy of the electron in Fig. 1 for electrons with $q=2$ and $g^*=0.44$ (the value in GaAs) for the barrier with $\lambda=14$ and $d=2$. It is clear that the transmission probability is significantly altered for all values of energy with the introduction of the $\mathbf{S}\cdot\mathbf{B}$ interaction. For most values of energy, the transmission probability is lowered by the $\mathbf{S}\cdot\mathbf{B}$ interaction.

The conductance $(G)$ of a tunneling structure can be computed in the ballistic regime as the average electron flow over half the Fermi surface[6] and is given by

$$G=G_0\int_{-\pi/2}^{\pi/2} T(E_F,\sqrt{2E_F}\sin\phi)\cos\phi \, d\phi, \tag{3}$$

where $E_F$ is the Fermi energy and $\phi$ is the angle between the direction of the incident electron and the $x$ direction. $G_0=e^2mv_Fl/\hbar^2$, where $v_F$ is the Fermi velocity and $l$ is the length of the structure in the $y$ direction. The conductance versus Fermi energy plot for electrons with $q=2$ and $g^*=0.44$ for the structure discussed in the previous paragraph is shown in Fig. 2. The conductance is normalized with respect to $G_0$. The conductance is found to be less for

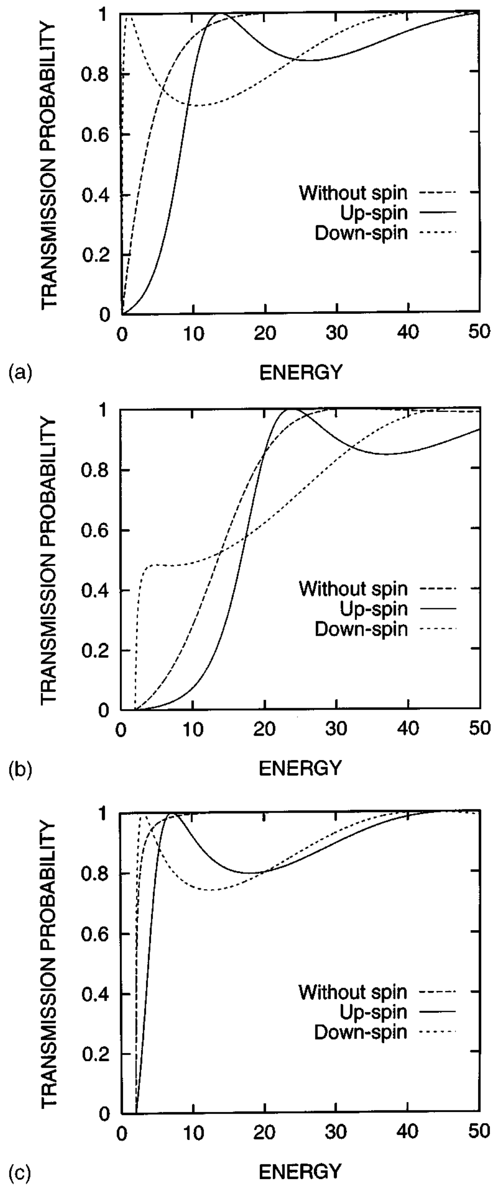


FIG. 3. Energy dependence of the transmission probability of an electron ($g^*=0.44$) through the magnetic barrier structure with $\lambda=14$ and $d=0.5$ for (a) $q=0$,(b)$q=2$, and (c) $q=-2$.

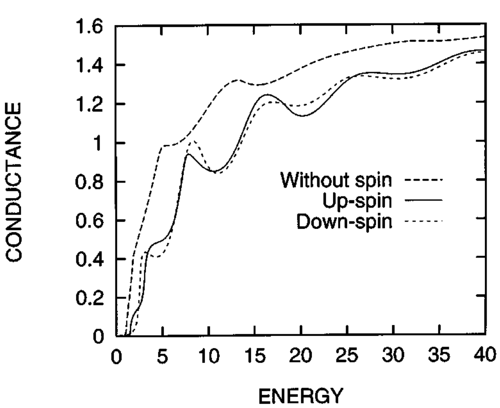


FIG. 2. Fermi energy dependence of the conductance $(G/G_0)$ of a device using the magnetic barrier structure with $\lambda=14$ and $d=2$.

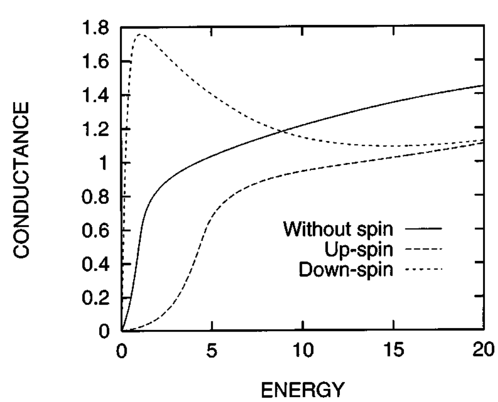


FIG. 4. Fermi energy dependence of the conductance $(G/G_0)$ of a device using the magnetic barrier structure with $\lambda=14$ and $d=0.5$.

both up-spin and down-spin electrons for the case with spin-magnetic-field interaction than the case without the interaction. This is expected since the transmission probability of electrons through the barrier is lowered in the presence of the $\mathbf{S}\cdot\mathbf{B}$ interaction. It is also interesting to note that the electrons exhibit larger oscillations in conductance.

We now study structures with closely spaced ferromagnetic stripes (thin barrier). We take $d=0.5$, $\lambda=14$ and $g^{*}=0.44$ for the analysis. The transmission probability for down-spin electrons is found to be much larger than that of the up-spin electrons for small electronic energies as depicted in Fig. 3 for different values of $q$. This difference in the transmission probability shows up in the $G-E_F$ characteristic as shown in Fig. 4. For $E_F<3$, the conductance of the down-spin electrons is more than 10 times larger than that of the up-spin ones. Thus, this structure exhibits spin-filtering properties for low Fermi energies and filters out down-spin electrons. It is also found that as $d$ increases, the ratio of the conductance of the down-spin electrons to that of the up-spin electrons decreases and thus, the structure loses its spin-filtering property. For a 2DEG in GaAs, $l_B=575$ Å and $\hbar\omega_c=0.34$ meV for $B_0=0.2$ T. Thus, the spin filter could be realized for structures with $d\leqslant 300$ Å and $E_F\approx 1.2$ meV.

In conclusion, we have shown that the presence of the interaction of the intrinsic spin of the electron with a magnetic field significantly changes the transmission probability of two-dimensional electrons through magnetic barriers and the conductance of devices consisting of such barriers. We have also exhibited the spin-filtering properties of such structures with thin barriers, i.e., closely placed ferromagnetic stripes.


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