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# Wave-Vector and Temperature-Dependent Electron Transport in a Magnetic Nanostructure Modulated by Bias*

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***Abstract*** *We theoretically investigate the wave-vector and temperature-dependent electron transport in a magnetic nanostructure modulated by an applied bias. The large spin-polarization can be achieved in such a device, and the degree of spin-polarization strongly depends on the transverse wave-vector and the temperature. These interesting properties may be helpful to spin-polarize electrons into semiconductors, and this device may be used as a spin filter.*

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**Key words:** magnetic nanostructure, spin-polarization, spin filtering

## 1 Introduction

The idea of spintronics is to manipulate the electron spin to represent digital information, and to fabricate ultimately spin-based semiconductor devices.[1−2] The realization of spintronic devices relies on the ability to inject spin-polarized current into a semiconductor from either magnetic semiconductor or ferromagnetic metal, which is one of the crucial ingredients for a functional spintronic device.[3−4] However, an efficiency of spin injection through ideal semiconductor/ferromagnetic interface is disappointingly small due to the large conductivity mismatch.[5−6] The use of spin filters is, therefore, an alternative approach, which can significantly enhance spin injection efficiencies.[7−8]

Recently, the electron-spin filtering in magnetically modulated nanostructures has received a lot of attention. Experimentally, the attractive proposal for spintronic devices has been given to exploit a single ferromagnetic stripe on top of a two-dimensional electron gas (2DEG).[9−10] In theory, several groups have widely investigated spin effects on electronic tunneling through such a device, and many interesting results were obtained from numerical calculations.[11−12]

Very recently, it is found that the device possesses the considerable spin-polarization if two $\delta$-function magnetic fields have unidentical strengths.[13] In order to enhance the spin effect, in this paper we study the nanostructure with an applied bias and two antiparallel $\delta$-function magnetic fields. It is found that the large spin-polarization can be achieved in such a structure, and the degree of spin-polarization strongly depends on the transverse wave-vector and the temperature. Therefore, a bias-tunable spin-polarized source is desirable for spintronic applications.[14]

## 2 Theoretical Method and Formulas

The proposed electron-spin filter is composed of a 2DEG in the $xy$ plane modulated by a perpendicular inhomogeneous magnetic field in the $z$ direction as plotted in Fig. 1, which may be realized via the Meissner effect of a superconductor on the top of 2DEG[15] or by depositing two ferromagnetic (FM) stripes on the top and bottom of a semiconductor heterostructure, and the magnetization directions of the FM stripes are arranged to be antiparallel.[16−17] Applying a bias voltage ($V_a$) across the 2DEG induces a triangular electrical potential $U(x)$, if we assume a uniform resistivity within the 2DEG. For simplicity, the magnetic field profile we consider is of delta function type, and it can be expressed as $\mathbf{B} = B_z(x)\mathbf{z}$ with $B_z(x) = B[\delta(x) + \delta(x - L)]$, where $B$ denotes the strengths of the magnetic fields and $L$ is the separation between the two magnetic fields.

Applying the single particle effective mass approximation, the Hamiltonian of the system can be described as

$$H = \frac{1}{2m^*}[\mathbf{p} + e\mathbf{A}(x)]^2 + \frac{eg^*}{2m_0}\frac{\sigma\hbar}{2}B_z(x) + \frac{eV_a}{L}x\,, \quad (1)$$

where $m^*$ and $m_0$ are the effective and real mass of the electron, $\mathbf{p}$ is the momentum of the electron, $g^*$ is the effective Lande factor, $\sigma = +1/-1$ is for up/down spin electrons, and $\mathbf{A}(x) = [0, A_y(x), 0]$ is the magnetic vector potential given in the Landau gauge, i.e.,

$$A_y(x) = \begin{cases} 0\,, & x < 0\,, \\ B\,, & 0 < x < w\,, \\ 2B\,, & x > w\,, \end{cases} \quad (2)$$

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which results in $B_z(x) = dA_y(x)/dx$.[18] For simplicity, we introduce two characteristic parameters: the frequency $\omega_c = eB_0/m^*$, where $B_0$ is some typical magnetic field and the length $l_B = \sqrt{\hbar/eB_0}$, so that we can express all the relevant quantities in dimensionless units: (i) the energy $E \to \hbar\omega_c E\ (= E_0 E)$, (ii) the bias voltage $V_a \to (\hbar\omega_c/e)V_a$, (iii) the coordinate $\mathbf{r} \to l_B\mathbf{r}$, (iv) the vector potential $\mathbf{A}(x) \to B_0 l_B \mathbf{A}(x)$, and (v) the magnetic field $\mathbf{B}_z(x) \to B_0\mathbf{B}_z(x)$. For GaAs and an estimated $B_0 = 0.1$ T, we have $l_B = 813$ Å, $\hbar\omega_c = 0.17$ meV, and $g^* = 0.44$.

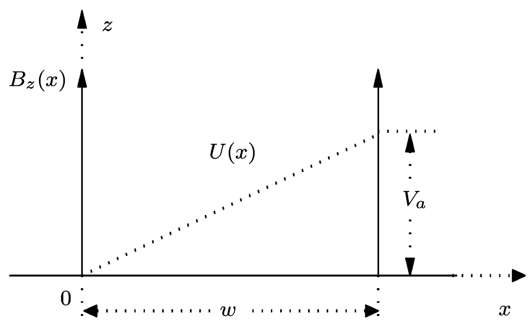


**Fig. 1** The magnetic nanostructure modulated by the bias. Here, we take $w = 4$, $V_a = 4$, and $B = 4$.

Because of the translational invariance of the system along the **y** direction, the total electronic wave-function can be written as $\Psi_{\rm left}(x, y) = e^{ik_y y}(e^{ik_{\rm left}x} + \gamma e^{-ik_{\rm left}x})$, $x < 0$, and $\Psi_{\rm right}(x, y) = \tau e^{ik_y y} e^{ik_{\rm right}x}$, $x > w$, here $\gamma/\tau$ denotes the reflection/transmission amplitude. Therefore, with the help of the transfer matrix method, we can obtain the $V_a$-dependent transmission probability for incident electron with energy $E$, wave vector $k_y$, and spin orientation $\sigma$ by $T(E, k_y, \sigma, V_a) = (k_{\rm right}/k_{\rm left})|\tau|^2$, to evaluate the spin splitting, we define the spin-polarization $P_T$ as below

$$P_T = \frac{T(E, k_y, +1, V_a) - T(E, k_y, -1, V_a)}{T(E, k_y, +1, V_a) + T(E, k_y, -1, V_a)}\,, \qquad (3)$$

where $T(E, k_y, +1, V_a)$ and $T(E, k_y, -1, V_a)$ are the transmission properties of electrons with spin up and down, respectively.

In order to further study the spin-injection in the structure, we define the electric conductance through the structure, which expresses the average electron flow over half of the Fermi surface at zero temperature[19]

$$G_\sigma = \frac{G_0}{2}\int_{-\pi/2}^{\pi/2} T(E_F, \sqrt{2E_F}\sin\phi, \sigma, V_a)\cos(\phi)d\phi\,, \quad (4)$$

where $G_0 = e^2 m^* \upsilon_F L_y/\hbar^2$, $E_F$ is the Fermi energy, $\upsilon_F$ is the velocity corresponding to $E_F$, $L_y$ is the length of the barrier structure in the $y$ direction, and $\phi$ is the angle of incidence relative to the $x$ direction. Then the spin-polarization $\mathrm{P_G}$ of electron conductance in the structure is defined by $P_G = (G_+ - G_-)/(G_+ + G_-)$. Here, $G_+$ and $G_-$ are the conductance for spin-up and spin-down electrons, respectively, and $P_G$ expresses the relative spin conductance excess at the Fermi energy, i.e., for zero temperature.

## 3 Numerical Results and Discussions

We first plot the transmission coefficient as a function of the incident energy $E$ in Figs. 2(a)–2(c) corresponding to the transverse wave-vector $k_y = -4$, 0, and 4, respectively. From Fig. 2, it can be obviously seen that there exists a more remarkable discrepancy in the transmission for electrons with opposite spin orientations. This is to say, the significant spin splitting of the transmission spectra appears in such a nanostructure, irrespective of the wave-vector component $k_y$. The resonant peaks shift towards lower energy region for the spin-down electrons and towards higher energy direction for the spin-up electrons. This feature can be ascribed to the dependence of effective potential,

$$U_\sigma(x, k_y) = [\hbar k_y + eA_y(x)]^2/(2m^*) + eg^*\sigma\hbar B_z(x)/(4m_0) + (eV_a/L)x\,,$$

of the magnetic-barrier structure on the wave-vector $k_y$ and the electron-spins $\sigma$. It also can be clearly seen that the degree of spin splitting of electronic transmission is strongly dependent on the wave-vector $k_y$, which is also a consequence of the variation of the effective potential $U_\sigma(x, k_y)$ due to the different $k_y$ values. This character can be seen more clearly from the inset, which shows the spin-polarization of transmitted beams. The degree of spin-polarization apparently decreases with the increase of the wave-vector $k_y$.

Next we turn to study the electron conductance and its polarization as shown in Fig. 3. From Fig. 3, it is clearly found that the main feature of the electron transmission, i.e., the spin splitting appears in conductance in such a nanostructure, despite the averaging of spin-dependent transmission probability over half the Fermi surface. The conductance of spin-up electrons is obviously different from that of spin-down electrons, where the dotted curve shifts towards the lower energy region, while the solid curve shifts towards the higher energy direction. Due to the great spin-splitting of the conductance, the obvious spin-conductance polarization effect will occur in such a magnetic nanostructure. This can be clearly seen from the curve of spin-conductance polarization $P_G$. Compared with the spin-polarization of transmitted beams $P_T$ for $k_y = 0$, the conductance polarization $P_G$ takes the similar shape, which is due to the fact that the conductance is obtained by integration of the electron transmission over the incident angle as in Eq. (4).

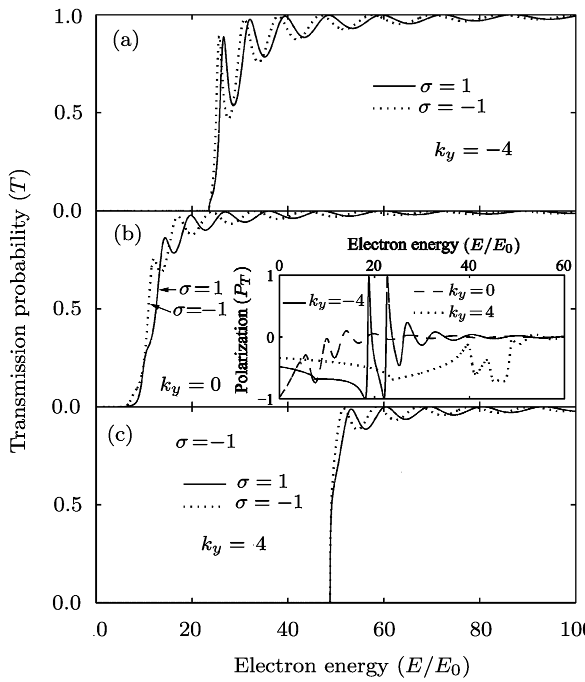


**Fig. 2** Energy dependence of the transmission probability of an electron with (a) $k_y = -4$, (b) $k_y = 0$, and (c) $k_y = 4$, where spin polarization $P_T$ is plotted in inset.

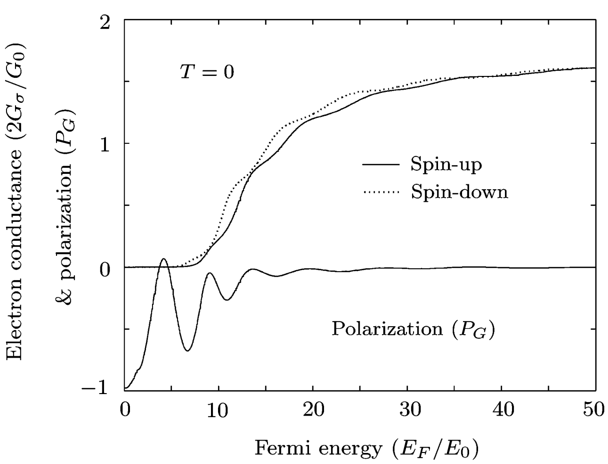


**Fig. 3** The electron conductance and polarization $P_G$ as a function of Fermi energy for $T = 0$.

At last, in order to generalize our results to nonzero temperature, we have to replace any function of $G(E_F)$ which depends on the Fermi energy $E_F$ by the corresponding average over the derivative of the Fermi function:

$$G(\mu) = \int d\varepsilon G(\varepsilon)(-\partial f_0/\partial \varepsilon)\,,$$

where

$$f_0 = \{\exp[(\varepsilon - \mu)/k_B T] + 1\}^{-1}\,.$$

In Fig. 4, we plot the conductance as a function of Fermi energy. From the figure, it can be obviously seen that the conductance increases with the increase of the Fermi energy. For the higher temperature, the conductance has smaller magnitudes of the oscillations, i.e., the finite temperatures smoothen the zero-temperature results, so we can expect that the oscillations will disappear when the temperature is high enough. Another interesting phenomenon could be seen that the conductance curves of spin-up electrons or spin-down electrons intersect at the same Fermi energy for the different temperatures at low Fermi energy. In order to see more clearly the effect of temperature on the electron conductance, the conductance polarization $P_G$ is plotted in inset. It is obviously find that the degree of spin-conductance polarization decreases with the increase of the temperature, so it can be expected that the conductance polarization will disappear in this nanostructure when the temperature is high enough.

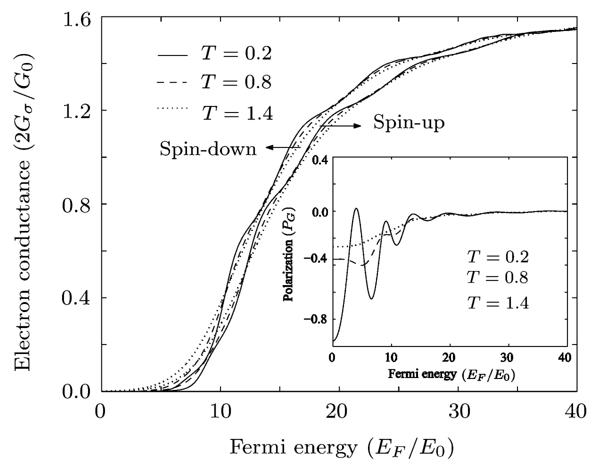


**Fig. 4** The temperature-dependent conductance of electron versus the Fermi energy. Inset is its polarization $P_G$.

## 4 Summary and Conclusion

In this paper, the wave-vector and temperature-dependent electron transport has been theoretically investigated in a magnetic nanostructure modulated by an applied bias. We find that the large spin-polarization can be achieved in such a device, and the degree of spin-polarization strongly depends not only on the transverse wave-vector but also on the temperature. These interesting properties may be helpful to spin-polarize electrons into semiconductors, and this device may be used as a spin filter.

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