Quantum tunneling in a hybrid magnetic-electric barrier

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Quantum tunneling in a hybrid magnetic-electric barrier

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We investigate the spin-dependent tunneling properties of a hybrid magnetic-electric barrier, where the two δ-function magnetic fields point in opposite direction and have different strength. It is found that even without any external electric field, such an asymmetric system shows spin-filtering features, which can be explained by the asymmetry of the effective potential of the corresponding structure. The spin polarization shows some oscillations and its magnitude can be adjusted by the electric barrier within the system. In addition, we found that if the distribution of the inhomogeneous magnetic field meets $\vec{B}(-x) = -\vec{B}(x)$, electrons cannot exhibit spin polarization under zero electric field, otherwise, electrons exhibit spin polarization even without electric field.

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I. INTRODUCTION

The electronic tunneling properties of magnetically modulated two-dimensional electron gas (2DEG) have been extensively studied [1-11]. The modulating magnetic field is inhomogeneous on the nanometer scale, which can be realized by depositing magnetic dots, ferromagnetic materials and type II superconductors on the surface of 2DEG. Theoretical studies on 2DEG system consisting of magnetic barriers have shown that the electronic tunneling through such a system is an essentially two-dimensional problem and depends on the transverse incident wave vector [7-11]. In early studies, researchers ignored the effect of the interaction between the intrinsic electronic spin and the inhomogeneous magnetic field. Majumdar first noticed the fact and studied the effects of electronic spin on the tunneling through magnetic barriers, where the two δ-function magnetic fields point in opposite direction. The results showed that under zero bias such structures possess the ability to distinguish the electronic states with different spin orientation [12]. Dobrovolsky et al. [13] and Guo et al. [14] further discussed the spin-dependent effect in relatively complicated magnetic-barrier structures. Recently, Papp et al. proposed a hybrid magnetic-electric barrier, where the two δ-function magnetic fields point in opposite direction and have the same strength, and discussed the spin-dependent tunneling through it [15]. However, following works have confirmed that the results presented by Majumdar [12] and Papp et al. [15] were not correct because of similar mistake made in their derivation of the formula of the transmission coefficient [16-18]. For simplicity, in the following discussion we will refer to the structure proposed by Papp et al. as MEB-I. It has been clarified that under zero bias, MEB-I structure does not possess spin filtering property [16-18]. In addition, Guo et al. found interesting resonant enhancement and negative differential resistance in such a hybrid structure in the presence of the external electric field [19], and further investigated the electric field effect on spin-dependent tunneling through MEB-I [20]. It is shown that the external electric field can make such a system spin-filtering [20].

In the present work, we go further to consider spin-dependent transport through a hybrid magnetic-electric barrier, where the two δ-function magnetic fields point in opposite direction and have different strength. For simplicity, we will refer to the structure as MEB-II in our paper. Our results indicate that even without any applied external electric field, the proposed MEB-II structure exhibits spin-dependent tunneling feature. We also sum up a simple rule on the relationship between the spin polarization and the inhomogeneous magnetically modulated structure.

II. THEORETICAL METHOD

The system considered here consists of a two-dimensional electron gas in $(x, y)$ plane, which is modulated by a magnetic field $\vec{B}$ in the $z$ direction and an electric potential. We depict the configuration of the magnetic field and the vector potential of our system in Fig. 1. In this model, we simplify the electric potential as a rectangular electric barrier $U(x)$, with $U(x) = U\Theta(L/2 - |x|)$, and take the δ-function magnetic field $\vec{B} = B_z \hat{z}$, with $B_z = B_1 \delta(x + L/2) - B_2 \delta(x - L/2)$. According to the Landau gauge, the vector potential $\vec{A}(x)$ is given by $\vec{A}(x) = [B_1 \Theta(L/2 - |x|) - (B_2 - B_1) \Theta(x - L/2)] \hat{y}$. In the framework of single effective mass approximation, our system could be described by the Hamiltonian

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where \( p_x \) and \( p_y \) are electronic momentums in 2DEG plane, \( g^* \) is the effective Lande factor, \( \sigma = \pm 1 \) correspond to spin up/down electrons, respectively, \( m^* \) is the effective mass of electron, and \( m_0 \) is the mass of free electron. For convenience, we express the quantities in dimensionless units by introducing the cyclotron frequency \( \omega_c = eB_0/m^* \) and the magnetic length \( l_B = \sqrt{\hbar/eB_0} \). Now we obtain the relevant quantities in dimensionless units: (1) \( B_1(x) \to B_0B_1(x) \), (2) \( A(x) \to B_0d_BA(x) \), (3) \( x \to l_Bx \), (4) \( E \to \hbar\omega_cE \). In our calculation, we set \( B_0 = 0.2 \ T \), \( m^* = 0.067m_0 \), and \( g^* = 0.44 \).

Because the system is translational invariant along the \( y \) direction, the solution of the two-dimensional Schrödinger equation

\[
H = \frac{p_x^2}{2m^*} + \frac{[p_y + eA(x)]^2}{2m^*} + U(x) + \frac{eg^*\sigma\hbar}{2m_0}B_z(x),
\]

where \( p_x \) and \( p_y \) are electronic momentums in 2DEG plane, \( g^* \) is the effective Lande factor, \( \sigma = \pm 1 \) correspond to spin up/down electrons, respectively, \( m^* \) is the effective mass of electron, and \( m_0 \) is the mass of free electron.

For MEB-I, we plot the numerical results of the transmission coefficients in Fig. 2. The width of the electric barrier along \( x \) direction is taken as \( L = 0.5 \), and the heights of the electric barrier are taken as \( U = 0, 3, 6 \). We can see that shoulder shape appears in the transmission spectra. As the electric barrier increases, the shoulder become broader and shift to the higher-energy region. In comparison with the transmission characteristics revealed in MEB-I [17,18], one can see that the different configurations of the inhomogeneous magnetic field between MEB-I and MEB-II determine the essential difference of their spin-tunneling properties within them. As well accepted, under zero bias there is no spin polarization in MEB-I [17,18,20]. Our results demonstrate that even under zero bias MEB-II does possess spin polarization although the polarization is relatively weak. The results can be easily understood by analyzing the effective potential of the corresponding structure. The interaction between the electronic intrinsic spin and the inhomogeneous magnetic field leads to different boundary conditions for tunneling electrons with different spin orientation. For MEB-I, \( U_1(x, k_y) = U_1(-x, k_y), i.e., spin-up electron tunneling along +x direction is equivalent to spin-down electron tunneling along the opposite direction. As well known, the transmission coefficients are the same for a particle tunneling through a given quantum potential along opposite directions, thus there is no spin polarization in the MEB-I structure. However, the MEB-II structure does not possess the above mentioned symmetry of the effective potential. Therefore, it exhibits the ability of spin filtering even under zero bias.

Although there are many published works discussed the spin polarization in magnetically modulated quantum structure [12,15-18], we found that there is not any general rule to describe the relationship between the spin polarization and the magnetic-barrier structure. By examining spin tunneling through kinds of the magnetic-barrier structures, we sum up a simple rule to generalize the relationship between the spin polarization and the distribution of the inhomogeneous magnetic field. In the magnetic-barrier structure where the inhomogeneous magnetic fields point in opposite direction and have same strength, electrons do not exhibit spin polarization under zero bias. However, the external electric field can make such a structure spin polarized. In the nanostructures with symmetric magnetic field with respect to the magnetic-modulation direction or asymmetric magnetic fields with different strength, electrons can exhibit spin polarization even under zero bias. When the electric field is applied, the status of the spin polarization can be greatly changed. By summing up the above analysis, we found that if the distribution of the inhomogeneous magnetic field meets \( B(-x) = -B(x) \), electrons cannot exhibit spin polarization under zero external electric field, otherwise, electrons exhibit spin polarization even without electric field.

Fig. 3 shows the variation of the conductance versus Fermi energy. The coefficients \( B_1 \) and \( B_2 \) in the magnetic distribution function are set to be 3 and 6, respectively, the length of the structure along \( x \) direction is taken as \( L = 0.5 \), and the heights of the electric barrier within the structure are taken as \( U = 0, 3, 6 \). It is evident that in the lower Fermi energy region, the conductance increases more sharply than in the higher Fermi energy region. The presence of the electric barrier obviously depresses the conductance of tunneling electrons. We can also observe that there is some difference between the conductance of the spin-up electrons and that of the spin-down
electrons, and the difference is dependent on the height of the electric potential barrier and the Fermi energy. Here the results once again demonstrate that the MEB-II structure possesses spin polarization even under zero bias. It would be helpful if we show the degree of spin polarization even under zero bias. It is obvious that the pronounced oscillations occur in the lower Fermi energy region. In the higher Fermi energy region, the oscillations become weak and approach zero. One can also notice that the electric potential barrier affects the degree of spin polarization. When we change the height of the electric barrier, not only the position of polarization peak and minima but also the amplitude of the oscillation is altered. For higher electric barrier, the peak and the minima of the spin polarization correspond to higher Fermi Energy.

**IV. CONCLUSIONS**

Based on the method of the transfer matrix, we investigated the spin-dependent tunneling of two-dimensional electrons through a hybrid magnetic-electric barrier (MEB-II), where the two \( \delta \)-function magnetic fields point in opposite direction and possess different strength. Different from MEB-I where the two magnetic fields possess equal strength, the MEB-II structure exhibits spin-filtering property even under zero bias. Spin polarization in MEB-II shows evident oscillation in lower Fermi energy region and its oscillation is also dependent on the electric barrier within the system. In addition, we sum up a simple rule to describe the relationship between the spin polarization and the distribution of the inhomogeneous magnetic fields.

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FIG. 1. The configuration of the inhomogeneous magnetic field and the vector potential for spin-up and spin-down electrons.

FIG. 2. Energy dependence of the transmission coefficient through MEB-II. \( g^* = 0.44, L = 0.5, B_1 = 3, B_2 = 6, \) and \( U = 0, 3, 6, \)

FIG. 3. Conductance as a function of the Fermi energy for electrons tunneling through MEB-II. \( U = 0, 3, 6, B_1 = 3, B_2 = 6, L = 0.5, \)

FIG. 4. Spin polarization as a function of the Fermi energy for electrons tunneling through MEB-II. \( U = 0, 3, 6, B_1 = 3, B_2 = 6, L = 0.5. \)
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