Electron-spin polarization in magnetically modulated quantum structures

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The spin-dependent electron resonant tunneling through magnetically modulated quantum structures has been investigated with and without an external electric field. The spin polarization is found to be strongly dependent on the magnetic configuration, the applied bias, the incident electron energy, and the incident wave vector. It is shown that an unpolarized beam of conducting electrons can be strongly polarized for an electron tunneling through magnetic-barrier structures, which is an arrangement with unidentical magnetic barriers and wells. The external electric field greatly changes the spin polarization of electrons for small electronic energies, where the electron-spin polarization exhibits considerable wave-vector-dependent features.

I. INTRODUCTION

Recently, physical properties and potential applications of magnetically modulated quantum structures call increasing attention. Many quantum systems (magnetic dots, antidots, steps, wells, barriers, periodic, and quasiperiodic superlattices) have been proposed and realized.[1–12] These systems greatly widen the field of the low-dimensional quantum systems. For example, Matulis *et al.*,[4] proposed new magnetic-barrier (MB) tunneling structures that can be realized experimentally by depositing ferromagnetic conducting or superconducting stripes on the surface of the heterostructures. In these MB structures, the quantum transport is an inherently two-dimensional process and possesses wave-vector filtering properties.[4,6–8] More recently, interest in electronic-spin polarization in a solid-state system has grown,[13–30] fueled by the possibility of producing efficient photoemitters with a high degree of polarization of the electron beam, creating spin memory devices[21] and spin transistors[22] as well as exploiting the properties of spin coherence for quantum computation.[23,24] The idea of electronic devices that exploit both the charge and spin of an electron for their operation has given rise to the new field of "spintronics," literally spin electronics,[25] in which the direction an electron spin is pointing is just as important as its charge. However, although there exists a wealth of studies on electron spin in semicondutor heterostructures and ferromagnetic metals, few investigations deal with electron-spin problem in magnetically modulated quantum structures.[11] Therefore, a detailed analysis to clarify and to evaluate the effect magnitude is greatly desired. In this paper, we pay attention to spin-dependent quantum tunneling through magnetically modulated structures. The interesting interaction of electron spin with inhomogeneous magnetic field will be investigated and the important role played by the external electric field will be examined through which the essential features of the spin-polarization are revealed.

II. THEORY

We start from the two-dimensional electron gas (2DEG) in the (x,y) plane subject to a perpendicular magnetic field (along the z direction) and an external electric field. The magnetic field is taken homogeneous along the y axis and varies along the x axis, while the electric field F is along the x direction. A MB quantum structure can be obtained with arranging identical building blocks A or with arranging two different building blocks A and B (Ref. 6) as depicted in Fig. 1, each of which consists of one magnetic barrier [with height B_i and width $d_i(i=1,2)$] and one magnetic well [with depth $-B_i$ and width $d_i(i=1,2)$]. The rectangular magnetic-field profile can be obtained in the limit of a small distance between the 2DEG and the ferromagnetic thin film.[12] Here in Sec. II, we constrict our theoretical analysis to the MB structure, which is an arrangement with two different blocks A and B. The formalism can be naturally extended to the MB structure of two identical blocks and to more complex MB structures. In magnetic barrier and magnetic well regions, the Hamiltonian of the system with the interaction between the electron spin and the inhomogeneous magnetic field is described by

$$H=\frac{1}{2m^*}[\mathbf{P}+e\mathbf{A}]^2+\frac{eg^*}{2m^*}\frac{\sigma\hbar}{2}B_z(x)-eFx, \qquad (1)$$

where m^* is the effective mass of the electron, e the proton's charge, $\mathbf{P}$ the momentum of the electron, g^* the effective g factor of the electron in a real 2DEG realized using semiconductor, $\sigma=\pm 1$ for the spin direction, and $\mathbf{A}=(0,A(x),0)$ is the Landau vector potential. We express quantities in dimensionless units by using the cyclotron frequency ω_c

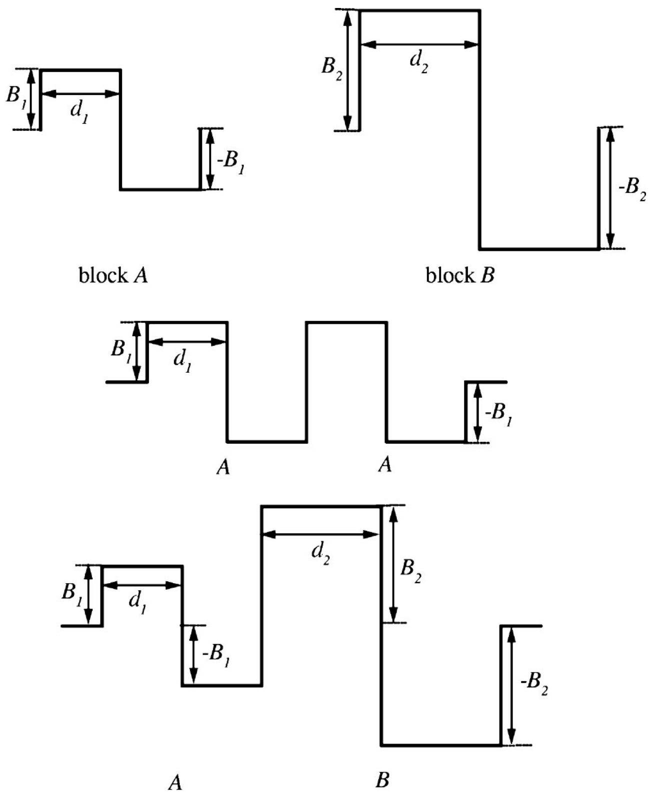

FIG. 1. Schematic representations of building blocks and two double magnetic-barrier structures.

$=eB_0/m^*$ and the magnetic length $l_B=\sqrt{\hbar/eB_0}$. For GaAs, $g^*=0.44$, m^* can be taken as $0.067m_e$ (m_e is the free electron mass) and an estimated $B_0=0.1$ T, we have $l_B=813$ Å and $\hbar\omega_c=0.17$ meV. The problem described by the above equation is translationally invariant along the y direction so that the total wave function can be written as a product $\Psi(x,y)=e^{ik_y y}\Phi(x)$, where k_y is the wave vector in the y direction. Accordingly, we obtain the one-dimensional (1D) Schrödinger equation as follows:

$$\left\{\frac{d^2}{dx^2}-[A(x)+k_y]^2-\frac{g^*\sigma B_z(x)}{2}+\frac{2eV_a x}{L_x}+2E\right\}\Phi(x)=0, \tag{2}$$

where $V_a=FL_x$ is the applied bias with the length $L_x=2d_1+2d_2$ along the x direction. It is important to introduce the effective potential $U_\sigma(x,k_y,V_a)=[A(x)+k_y]^2/2+g^*\sigma B_z(x)/4-eV_a x/L_x$ of the corresponding structure, which depends not only on the magnetic configuration, the wave vector k_y, and the applied bias, but also on the interaction between the electron spin and the nonhomogeneous magnetic field. In the left and right regions, the wave functions can be written as $\Psi_l(x,y)=e^{ik_y y}(e^{ik_l x}+re^{-ik_l x})$, and $\Psi_r(x,y)=\tau_\sigma e^{ik_y y}e^{ik_r x}$, where $k_l=\sqrt{2E-[A_l(x)+k_y]^2}$, $k_r=\sqrt{2(E+eV_a)-[A_r(x)+k_y]^2}$, and τ_σ is the spin-dependent transmission amplitude. In these two regions, there is no magnetic field, so $A_l(x)=A_r(x)=0$. In the magnetic barrier and well regions, we can solve the 1D Schrödinger equation by using Hermitian functions.[6] Therefore, the spin-dependent transmission coefficient through the MB structure can be obtained by the standard transfer-matrix method, which is given by

$$T_\sigma(E,k_y,V_a)=\frac{k_r}{k_l}|\tau_\sigma|^2. \tag{3}$$

For MB structures consisting of identical building blocks with an external electric field, or MB structures of unidentical building blocks with or without an electric field, one can expect a difference between T_+ and T_- for the electron with the same E and k_y. To evaluate the electron spin-polarization effect, it is useful to calculate the spin polarization of the transmitted beam defined by

$$P(E,k_y,V_a)=\frac{T_+(E,k_y,V_a)-T_-(E,k_y,V_a)}{T_+(E,k_y,V_a)+T_-(E,k_y,V_a)}. \tag{4}$$

In the ballistic regime, the conductance G at zero bias can be calculated as the electron flow averaged over the Fermi surface to both spin directions

$$G(E_F)=\frac{G_0}{2}\sum_{\sigma=1,-1}\int_{-\pi/2}^{\pi/2}T_\sigma(E_F,\sqrt{2E_F}\sin\theta,0)\cos\theta d\theta, \tag{5}$$

where $G_0=e^2m^*v_FL_y/\hbar^2$, E_F the Fermi energy, v_F the velocity corresponding to E_F, and L_y the length of the structure in the y direction. Under an applied bias, the current density J_x can be derived from the transmission coefficient by

$$J_x=\sum_{\sigma=1,-1}J_0\int_0^\infty dE\sqrt{E}[f(E,E_F^l)-f(E,E_F^r)]\times\int_{-\pi/2}^{\pi/2}\cos\theta T_\sigma(E,\sqrt{2E}\sin\theta,V_a)d\theta, \tag{6}$$

where $J_0=e\sqrt{m_0^*}/2\sqrt{2}\pi^2\hbar^2$, $f(E,E_F^l)$ and $f(E,E_F^r)$ are the Fermi-Dirac distribution functions in the left and right electrodes. When $T=0$ K, the above equation reduces to $J_x=\Sigma_{\sigma=1,-1}J_0\int_{E_0}^{E_F}dE\sqrt{E}\int_{-1}^{1}T_\sigma(E,\overline{\theta},V_a)d\overline{\theta}$, where $E_0=(E_F-eV_a)\Theta(E_F-eV_a)$ and Θ is the step function.

III. RESULTS AND DISCUSSION

Figure 2 presents the spin polarization for electron tunneling through one MB structure, which is an arrangement with two identical blocks A with and without applied biases. Energy and eV_a are in units of $\hbar\omega_c$. It is known that the transmission coefficient through a potential barrier is equal for particles moving in opposite directions, i.e., the tunneling characteristics are invariant with respect to the replacement $x\to -x$ in the equation of motion. According to this invariance, $U_+(E,k_y,0)=U_-(E,k_y,0)$ for MB structures of identical building blocks leads to the independence of the transmission coefficient on the spin direction. Therefore, at zero bias this type of MB structure does not show up spin polarization and cannot possess spin-filtering properties, but the transmisssion is still different from the traditional description for electrons without consideration of the spin. Under an applied bias, for the case with the interaction between the intrinsic spin of electrons and the magnetic field, the transmission coefficient is significantly altered, so the electron shows up considerable spin-polarization, especially for small

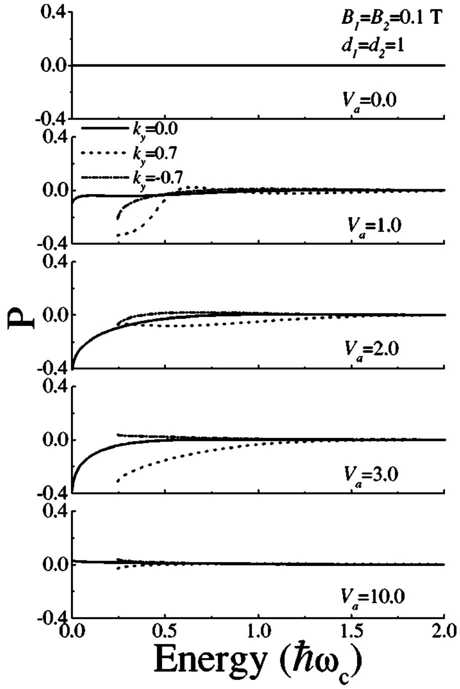

FIG. 2. Spin polarization for electron tunneling through one MB structure of two identical blocks A $(B_1=0.1\ \mathrm{T},\ d_1=1)$.

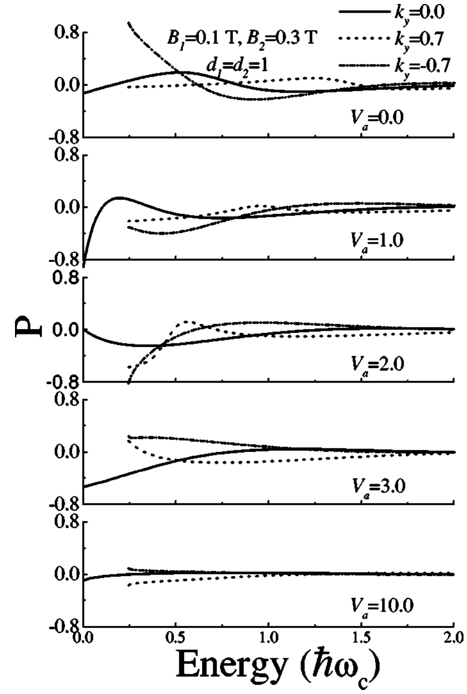

FIG. 3. Spin polarization for electron tunneling through one MB structure of two unidentical blocks A $(B_1=0.1\ \mathrm{T},\ d_1=1)$ and B $(B_2=0.3\ \mathrm{T},\ d_2=1)$.

electronic energies. For large electronic energy, the spin polarization is weakened, and finally approaches zero. Numerical results also indicate that for different wave vector k_y, the spin polarization is very different, and with the magnitude of wave vector k_y increasing, the spin polarization is strengthened. Moreover, upon further increasing the applied bias, the spin polarization smoothens.

Similar to asymmetric double-barrier semiconductor structures, the MB structure of two different building blocks also provides wider room for theoretical investigation and potential applications.[6–8] Studies have already indicated that this type of MB structure possesses stronger wave-vector filtering properties.[6–8] The results of the spin polarization are shown in Fig. 3. It is interesting to note that at zero bias, the electron shows stronger wave-vector-dependent spin-polarization for small electronic energies. Under the influence of the applied bias, the spin polarization changes greatly. Moreover, upon further increasing the applied bias, the spin polarization smoothens as that exhibited in Fig. 1. Here one may wonder why all calculations except the $k_y=0.0$ case stop near the incident energy 0.25 in unit of $\hbar\omega_c$ in both Fig. 2 and Fig. 3. Is there any numerical problem? We would like to point out that there is no numerical problem in our calculation. For considered incident wave vector $k_y=0.7$ and $k_y=-0.7$ cases, the corresponding energy E_y in the y direction equals 0.245. Therefore, the total incident electron energy must not be less than 0.245. In Figs. 2 and 3, the horizontal axis represents the total incident energy of the electron. Therefore, it seems that calculations for the $k_y=0.7$ and $k_y=-0.7$ cases stop near 0.25 in Figs. 2 and 3. Similar phenomena can also be seen in Fig. 4 of Ref. 4.

In order to further reveal the characteristics of the spin polarization in the magnetically modulated structure, Fig. 4 gives the results of the spin polarization versus the applied bias at certain incident energies $E=0.5,1.0$. We see that the spin polarization exhibits rapid oscillations. For small biases, the electron-spin polarization changes its sign quickly, and exhibits polarization-flip features. With the applied bias increasing, the spin polarization smoothens. In general, the magnitude of the oscillations decreases with the applied bias increasing. Further, as the incident energy increases, the magnitudes of the oscillations also decrease.

From Eq. (4), it is evident that the spin polarization $P=(T_+-T_-)/(T_++T_-)$ is determined not only by the trans-

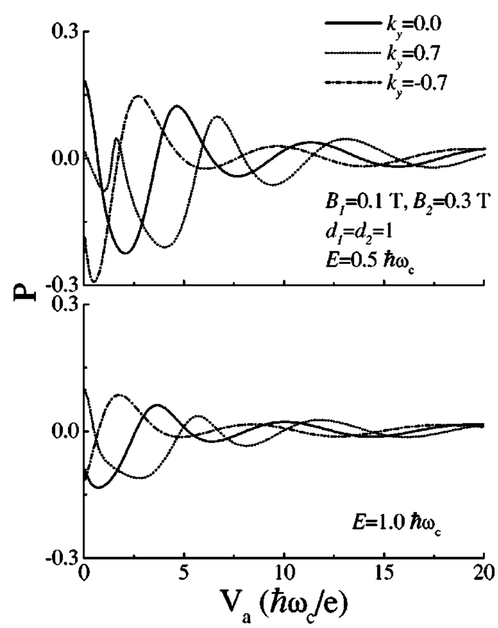

FIG. 4. Spin polarization versus the applied bias for electron tunneling through one MB structure of two unidentical blocks A $(B_1=0.1\ \mathrm{T},\ d_1=1)$ and B $(B_2=0.3\ \mathrm{T},\ d_2=1)$.

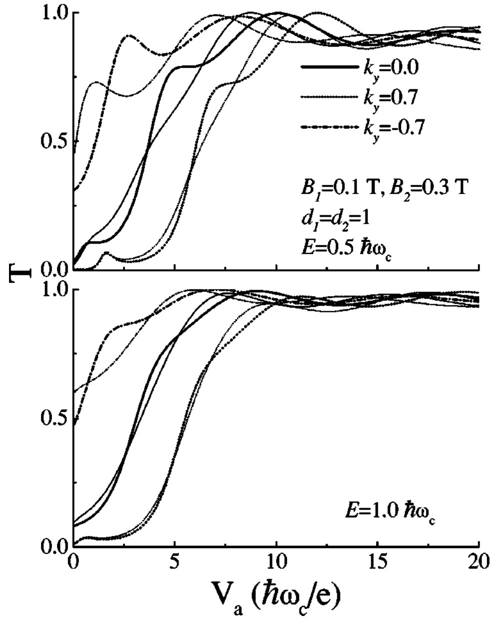

FIG. 5. Transmission versus the applied bias for electron tunneling through one MB structure of two unidentical blocks A ($B_1=0.1$ T, $d_1=1$) and B ($B_2=0.3$ T, $d_2=1$).

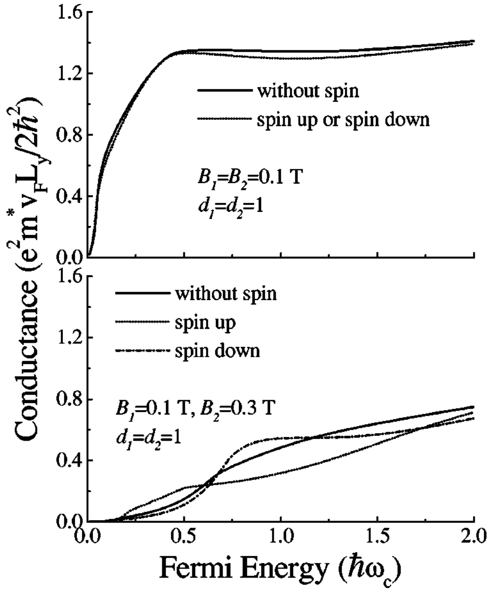

FIG. 6. The conductance for electron tunneling through two MB structures. (a) A ($B_1=0.1$ T, $d_1=1$); (b) A ($B_1=0.1$ T, $d_1=1$) and B ($B_2=0.3$ T, $d_2=1$).

mission coefficient versus the applied bias but also by the difference between T_+ and T_-. Keeping this fact in mind, we have no difficulty in understanding the oscillations appearing in the polarization versus the applied bias in Fig. 4. In order to better understand the oscillations appearing in the polarization, in Fig. 5 we display the transmission coefficient for electron tunneling through the magnetic-barrier structure at certain incident energies $E=0.5,1.0$. Thick solid, dotted, and dashed-dotted lines correspond to the spin-up case, while thin solid, dotted, and dashed-dotted ones correspond to the spin-down case. It is easily seen that in the both cases the variations of the transmission coefficient exhibit complex oscillations with the applied bias increasing, and for smaller incident electron energy, the oscillations become more complex. At some intervals of the applied bias, the transmission coefficient for the spin-up case is larger than that for the spin-down case (i.e., $T_+>T_-$), while at other intervals of the applied bias, the transmission coefficient for the spin-up case is less than that for the spin-down case (i.e., $T_+<T_-$). These complex variations of the transmission coefficient versus the applied bias for the spin-up and spin-down cases result in frequent change of the sign of the spin polarization. Therefore, in Fig. 4, one can see the rapid oscillations of the polarization.

From Fig. 2 to Fig. 4 one can conclude that a much larger spin polarization can be obtained with the MB structure of different building blocks. Contrary to the case of the MB structure of identical building blocks, this type of MB structure manifests dependence of the transmission coefficient on the electron-spin sign even without any external electric fields. By adjusting the electric field, we can control the magnitude of spin-polarization effect.

Finally, we examine the spin-polarization effect on the conductance and the current density. Figure 6 shows the results that the conductance versus Fermi energy without an applied bias at zero temperature, where the conductance is normalized with respect to $G_0/2$. The total conductance through the MB structure is the sum of the spin-up conductance and the spin-down conductance. For comparison, we drew the curve by taking half of the total conductance for the case without spin-magnetic-field interaction (see solid curve in Fig. 6). For the MB structure with two identical building blocks, the conductance is the same for both spin-up and spin-down electrons, and it is less than the case without spin-magnetic-field interaction. For the MB structure of two unidentical magnetic barriers, the conductance splitting occurs. There is obvious difference of the conductance between the spin-up case and the spin-down case. The conductance of spin-up electrons is larger than that of spin-down electrons

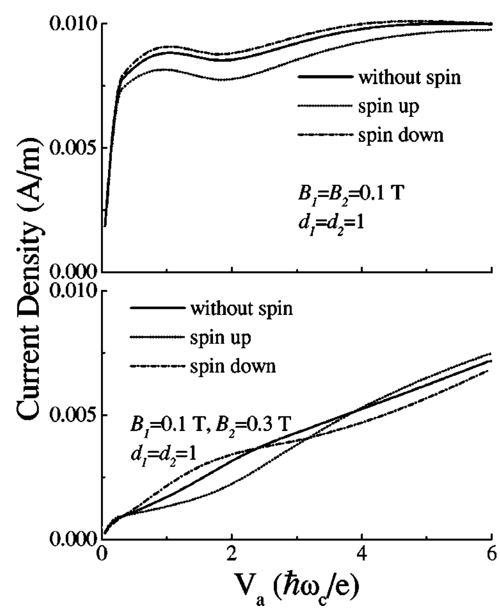

FIG. 7. The current density for electron tunneling through two MB structures. (a) A ($B_1=0.1$ T, $d_1=1$); (b) A ($B_1=0.1$ T, $d_1=1$) and B ($B_2=0.3$ T, $d_2=1$).

for small electronic energies, while for higher Fermi energies, the conductance decreases for both spin-up and spin-down cases than the case without the spin-magnetic-field interaction.

The current density J_x for electron tunneling through two MB structures is given in Fig. 7. The Fermi energy is set to be $E_F=0.6$. It is clear that J_x-V_a characteristic exhibits obvious negative-differential conductivity, and the current is suppressed drastically for electron transport through the MB structure of different building blocks due to the averaging of the transmission $T_\sigma(E,k_y,V_a)$. Moreover, the current splits and is significantly altered when the interaction between the electron spin and the inhomogeneous magnetic field is included. For the MB structure of identical blocks, the current density of spin-down electrons is larger than that of the case without the spin-magnetic-field interaction, while the current density of spin-up electrons is less than that of the case without the spin-magnetic-field interaction. For the MB structure of unidentical blocks, the variations of the current density are complicated and different among spin-up, spin-down, and without-spin cases.

IV. CONCLUSIONS

In conclusion, we demonstrated the dependence of spin polarization in the magnetically modulated quantum structure on the magnetic configuration, the applied bias, the incident energy, and the incident wave vector. Two major results have been obtained. One is the external electric field can play an important role on the spin polarization in the magnetically modulated quantum structure. The other is that in the MB structures of unidentical building blocks, the electron exhibits considerable spin polarization even without an applied bias, which can serve as a basis for the creation of quantum structures with new functions.

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