Vol 16 No 10, October 2007
1009-1963/2007/16(10)/3080-07

Chinese Physics

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The electron transport characters in a nanostructure with the periodic magnetic-electric barriers*

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(Received 21 January 2007; revised manuscript received 2 March 2007)

This paper detailedly studies the transmission probability, the spin polarization and the conductance of the ballistic electron in a nanostructure with the periodic magnetic-electric barriers. These observable quantities are found to be strongly dependent not only on the magnetic configuration, the incident electron energy and the incident wave vector, but also on the number of the periodic magnetic-electric barriers. The transmission coefficient and the spin polarization show a periodic pattern with the increase of the separation between two adjacent magnetic fields, and the resonance splitting increases as the number of periods increases. Surprisingly, it is found that a polarization can be achieved by spin-dependent resonant tunnelling in this structure, although the average magnetic field of the structure is zero.

Keywords: magnetic nanostructure, spin polarization, resonance splitting, wave-vector filtering
PACC: 7225, 7210, 7320C, 7200

1. Introduction

Recently, the electronic transport properties of semiconductor nanostructures in the presence of inhomogeneous magnetic fields have attracted much attentions, and many studies have been done. Experimentally, the inhomogeneous magnetic fields on the nanoscale scale have been realized with the deposition of type II superconducting materials on conventional heterostructures,[1] the patterning of ferromagnetic materials integrated with semiconductors,[2−4] and the creation of magnetic dots.[5−10] Also, an out-of-plane magnetization has been realized by the deposition of ultrathin layers of Fe on Ag.[11] In recent experiments the number of magnetic barriers has been decreased down to the least involved case of a single barrier.[12−14]

Theoretically, there have been a wealth of studies on the electron transport probabilities such as transmission probability, electron conductance and spin polarization as a degree of freedom in semiconductors.[15−19] In the magnetic barrier system, the electron transport is very different from that in the well-known potential barrier because the electron tunnelling is now a two-dimensional problem. The transmission not only depends on the energy of the incoming electrons but also on the direction in which the electrons move towards the barrier. Moreover, when not only the charge, but also the spin of the electrons is taken into account, the electronic transport can become spin-polarized.[20−26]

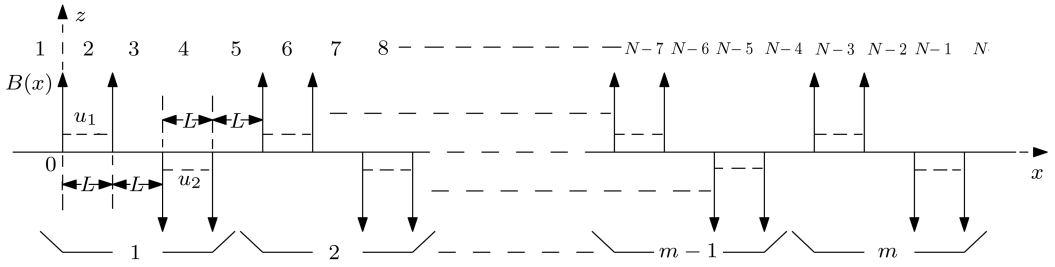


Fig.1. The model magnetic-electric barriers profile used in our calculation.

*Project supported by the Scientific Research Fund of Hubei Provincial Education Department (Grant No 080043).
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Although many studies have been done to exploit the electron transport probabilities in semiconductors both theoretically and experimentally, few interests have been directed towards the effect of the periodic magnetic-electric barriers on the electron transport. Thus, in this paper, we pay attention to the electron transport through the nanostructure with periodic magnetic-electric barriers as illustrated in Fig.1. A detailed-numerical analysis of the effect of the periodic magnetic-electric barrier on the electron transport leads to interesting features that may be of practical importance. From the calculations, some novel phenomena are found for the first time so far as we know.

2. Theoretical method and formulas

We consider a two-dimensional electron gas (2DEG) in the xy plane with the periodic magnetic-electric barriers that each period contains a double-pair of magnetic fields in the z direction and a pair of rectangular electric barriers as shown in Fig.1. The number of the periods is denoted by m. For simplicity, the magnetic field profile and the electric barrier profile which we consider are of delta function type and of Heaviside step function type respectively. For the first period, the magnetic field and the electric barrier have the following form: $\boldsymbol{B} = B_z(x)\boldsymbol{z}$ with $B_z(x) = B[\delta(L-2|x-L/2|)-\delta(L-2|x-5L/2|)]$ and $U(x) = u_1\theta(L-2|x-L/2|)+u_2\theta(L-2|x-5L/2|)$, where B gives the strength of the magnetic field and L is the separation between the two adjacent magnetic fields.

In single effective mass approximation, the Hamiltonian describing such a system without bias is

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

where m^* and m_0 are the effective and real mass of the electron respectively, g^* is the effective Landé factor, p is the momentum of the electron, $\sigma = +1/-1$ for up/down spin electrons, and $\boldsymbol{A}(x) = [0, A(x), 0]$ is the magnetic vector potential given in the Landau gauge. For simplicity, we introduce the dimensionless units, the electron cyclonic frequency $\omega_c = eB_0/m^*$ and the magnetic length $l_B = \sqrt{\hbar/eB_0}$ with B_0 as some typical magnetic field. We will express all the relevant quantities in dimensionless units: (1) the energy $E \to \hbar\omega_c E(= E_0 E)$, (2) the coordinate $r \to l_B r$, (3) the vector potential $\boldsymbol{A}(x) \to B_0 l_B \boldsymbol{A}(x)$, and (4) the magnetic field $\boldsymbol{B}_z(x) \to B_0\boldsymbol{B}_z(x)$. For GaAs and an estimated $B_0 = 0.1\,\mathrm{T}$, we have $l_B = 813\,\mathring{A}$, $\hbar\omega_c = 0.17\,\mathrm{meV}$, and $g* = 0.44$.

Because the system is translation invariant along the y direction, the wavefunction of electrons can be written as $\Psi_n(x,y) = \mathrm{e}^{\mathrm{i}k_y y}(A_n\mathrm{e}^{\mathrm{i}k_n x} + B_n\mathrm{e}^{-\mathrm{i}k_n x})$, here symbols $n = 1, 2, 3, \ldots, N$ and k_n denote the number of the areas divided by the magnetic fields and the longitudinal wave vector of the nth area respectively. Now we assume that the electron is only injected from the left, i.e. A_1=1 and B_N=0. Thus, using the transfer matrix method, the wave function and flux continuity across each boundary, we can obtain the coefficient A_N. Then the transmission probability is obtained:

$$T(E, k_y, \sigma) = \frac{k_N}{k_1}\left|A_N\right|^2, \quad (2)$$

and the electron spin polarization effect can be evaluated by calculating the polarization of the transmission probability, which is defined as

$$P_T(E, k_y) = [T(E, k_y, +1) - T(E, k_y, -1)]/[T(E, k_y, +1) + T(E, k_y, -1)], \quad (3)$$

here, $T(E, k_y, +1)$ and $T(E, k_y, -1)$ are the transmission probability of electron with spin up and down respectively.

When the electron transmission probability is obtained, the conductance G_σ can be calculated from the well-known Landauer–Buttiker formula:[27]

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

where $G_0 = e^2 m^* \upsilon_\mathrm{F} L_y/\hbar^2$, E_F is the Fermi energy, υ_F

is the velocity corresponding to E_F, L_y is the length of the barrier structure in the y direction, and ϕ is the angle of incidence relative to the x direction.

3. Numerical results and discussions

First of all, we investigate the transmission coefficient as a function of electron energy E. Figures 2(a)–2(c) correspond to $m = 1$, 2 and 3, respectively. It is evident that no resonance splitting occurs in each resonance peak for $m = 1$, and when one is added to m, the resonance splitting occurs one time in each resonance. As the number of m increases, the resonance splitting increases, so the total number of resonance peaks increases and peaks become sharper, when $m \to \infty$, they will fill the whole inner region of the miniband continuously. For the mth periodic magnetic-electric barriers tunnelling the splitting is $(m-1)$-fold. The splitting rule is exactly the same as that obtained in periodic electric barrier superlattices. From the figure, one also can find that transmission curves for spin up and down electrons are very similar, the only difference is that some resonant peaks for spin up electron shift to higher energy. Moreover, along with the increase of electron energy the resonant peaks become less sharp and widen, while the values of anti-resonant valleys are bigger, so we can expect the transmission coefficient will approach one without resonant peaks and anti-resonant valleys for enough high energy of electrons. Figures 2(d)–2(f) are the spin-polarization corresponding to Figs.2(a)–2(c) respectively. From the figures, one can clearly see that the polarization changes its sign rapidly with the low electron energy, and the polarization intensity becomes weaker with the increase of electron energy until it reaches zero when the electron energy is enough high. Obviously, it is the spin-splitting effect that provides a dependence of the electron-spin polarization of transmitted beams on the electron incident energy. The striking features just described are the important properties that should be explored experimentally, and are very helpful for developing spin-dependent fast tunnelling electron devices.

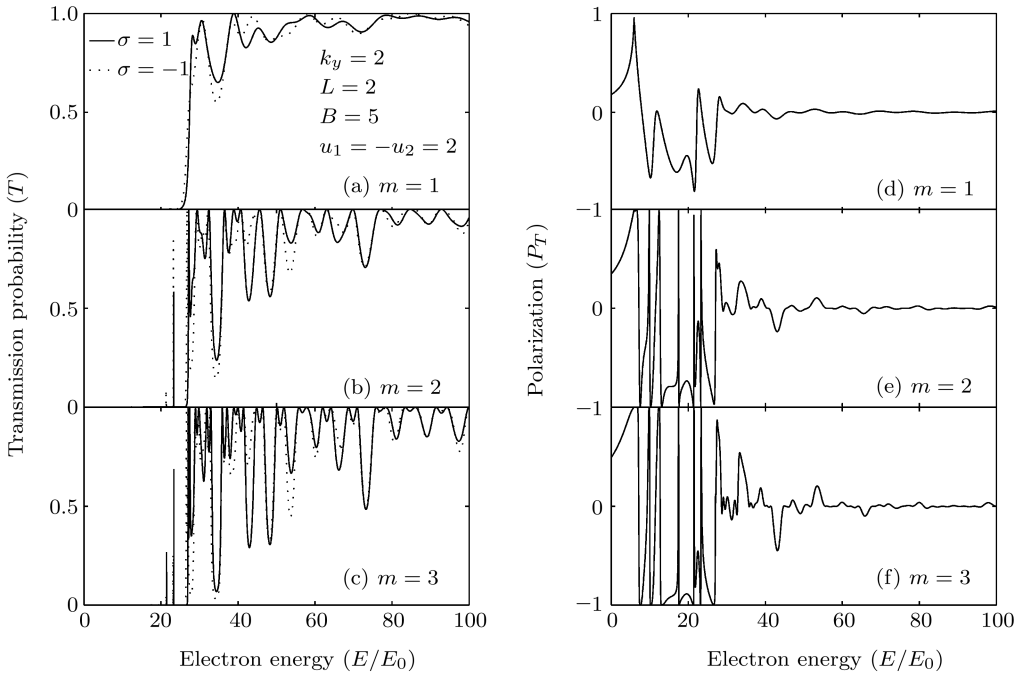


Fig.2. The transmission coefficient and the spin-polarization for the different number of the periodic magnetic-electric barriers as a function of the electron energy E.

Now we turn to study the dependence of the transmission probability on the incident wave vector in the y direction which are set to be $k_y = 0, \pm 2$ as shown in Figs.3(a)–3(c). one can easily see resonant peaks with unity value in the transmission spectrum. The positions of the resonant peaks display obvious wave-vector-dependent features. For $k_y < 0$, the resonant peaks are located both in the lower energy region

and in the higher energy region; while for $k_y > 0$, they are only in the higher energy region. In a word, with the increase of k_y the energy in which the resonant peaks locate is higher. From the figures one also can find that the curves for spin up and down electrons are very similar, the difference is that (1) in the lower energy region, for $k_y = -2$ there exist two line-shaped resonant peaks with unity values for spin down electron; for $k_y = 0$ there also exist two line-shaped resonant peaks for spin down electron, (2) some resonant peaks for spin up electron shift higher energy. In order to reveal the effect of k_y on the spin polarization, we plot Figs.3(d)–3(f) corresponding to Figs.3(a)–3(c) respectively. From the figures one can obviously find that with the decrease of k_y the polarization becomes smooth more quickly. Further, as the incident energy increases, the magnitude of the oscillations also decreases, for enough high energy it disappears, i.e., the polarization is zero.

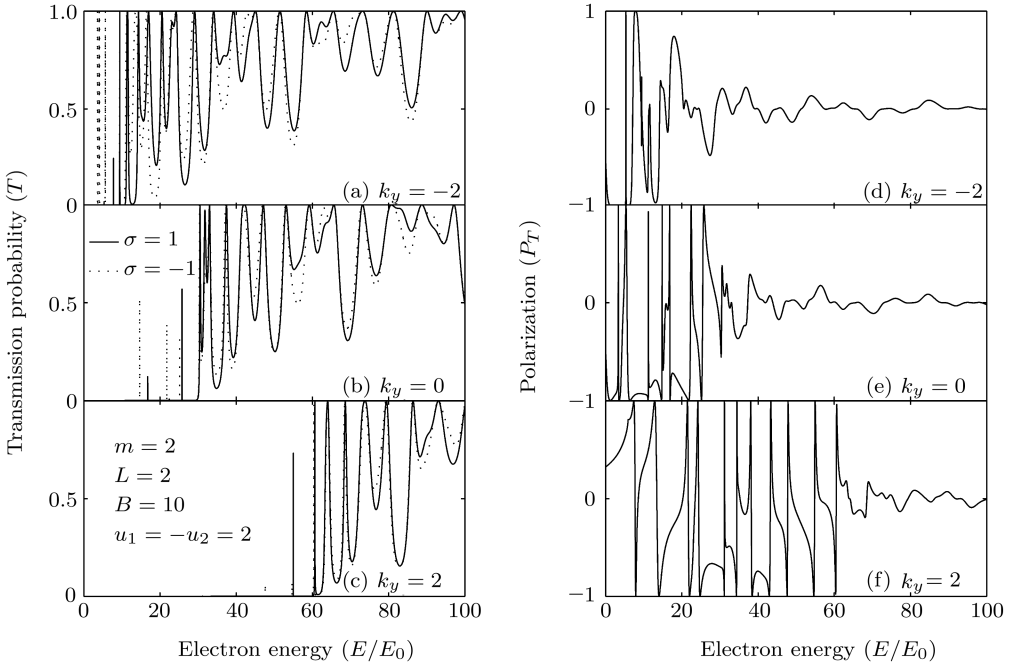


Fig.3. Energy dependence of the transmission coefficient and the spin-polarization on the incident wave vector in the y direction.

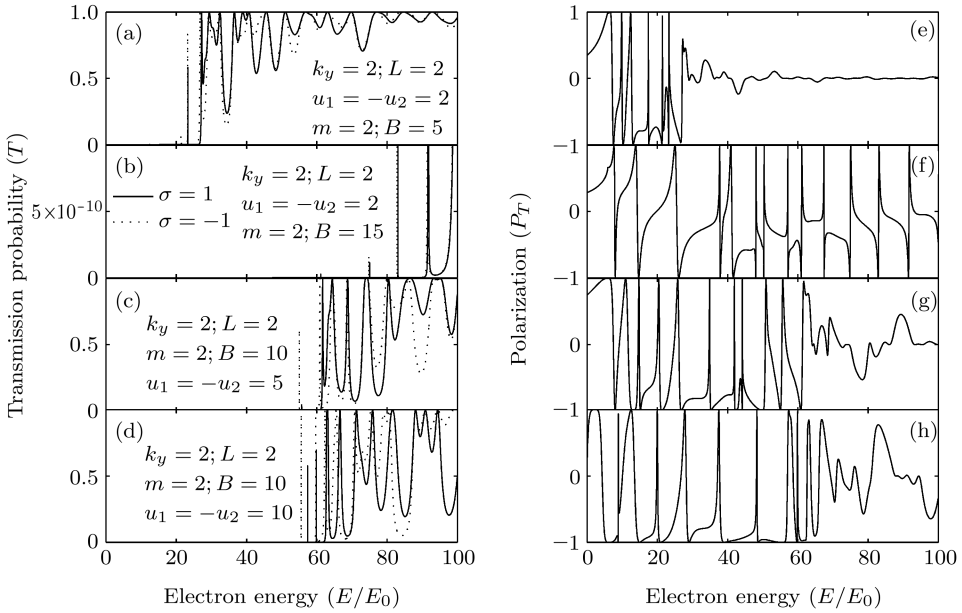


Fig.4. The transmission probability for the different magnetic fields and the different electric barriers. (e)–(h) are the spin-polarization corresponding to (a)–(d) respectively.

Figures 4(a)–4(d) give the transmission probability versus the incident energy for the different magnetic field and the different electric barrier. Figures 4(e)–4(h) display the spin polarization corresponding to Figs.4(a)–4(d) respectively. From Figs.3(c), 4(a) and 4(b) we find that with the increase of magnetic field, (1) the threshold $E_{\rm th}$ increases, (2) the resonant peaks become sharper. When the strength of the magnetic field is enough big the transmission approaches zero. For the energy $E < E_{\rm th}$, the spin polarization exhibits rapid oscillations, changes its sign quickly and reaches 100% in resonance; while for $E > E_{\rm th}$, it quickly becomes smooth. This phenomenon also can be seen from Figs.2 and 3. We ascribe the 100% polarization to the disappearance of the transmission for spin-down electron and the small transmission of electron with spin up which seems to be zero in the figure. Next we study the effect of the electric barrier on the electron transport as plotted in Figs.3(c), 4(c) and 4(d). These three figures tell us (1) the value of the electric barrier nearly does not change the threshold $E_{\rm th}$, this is different from the effect of the magnetic field; (2) for $E > E_{\rm th}$, the difference of the transmission for spin up and down electrons is more obviously with the increase of electric barrier. This point also can be seen from the spin polarization as shown in Figs.3(f), 4(g) and 4(h) which correspond to Figs.3(c), 4(c) and 4(d) respectively. From the spin polarization curves, one also find that the peaks become sparser with the increase of electric barrier.

Next, the transmission coefficient and the spin polarization are investigated as the function of L for the different energy of incident electron. Figures 5(d)–5(f) correspond to Figs.5(a)–5(c) respectively. First it is worthy to notice that the spin polarization and the transmission probability both exhibit periodic oscillation with the increase of L, here only about one period is given. From the figures, one can easily find that with the increase of incident energy, local minima of the transmission spectra become bigger and the period of polarization curve increases. The periodic oscillating behaviour can be generally interpreted as follows. The propagating and reflected waves having the same longitudinal wavenumber interfere with each other and form a standing wave inside each region of the bridge. When the phase shift between the incident wave and the reflected wave is just equal to $2n\pi$, the transmission will be reinforced, and while the phase shift is $(2n+1)\pi$, the transmission will be reduced. The two conditions correspond to the maximum and minimum of the transmission spectra respectively. Consequently, a periodic oscillation appears in the transmission profile.

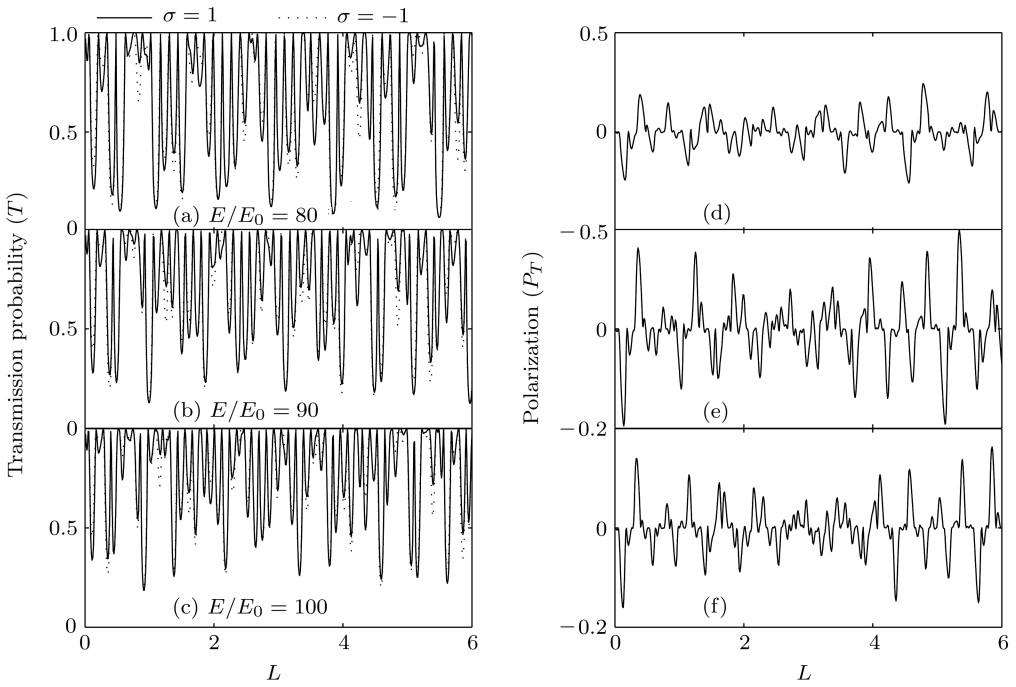


Fig.5. The transmission coefficient and the spin-polarization versus L for the different electron energy E. (d)–(f) correspond to (a)–(c) respectively.

Finally, we discuss the conductance of electron when the electric barrier and magnetic field are changed. In Fig.6 we present the effect of the electric barrier on the electron conductance. It is evident that (a) the conductance displays some oscillations with small magnitudes in the high energy and big magnitudes in the low energy, (b) with the increase of electric barrier, the threshold $E_{\rm th}$ and the onset of the conductance for spin up and down electrons both increase. Figure 7 shows the conductance as a function of the incident electron energy for the different magnetic field. It can be easily seen that (1) as the incident electron energy increases, the conductance also exhibits some oscillations with big magnitudes in the low energy and small magnitudes in the high energy, (2) with the increase of the strength of magnetic field, the conductance and its difference for spin up and down electrons drastically decrease in the low energy, while the threshold $E_{\rm th}$ obviously increases.

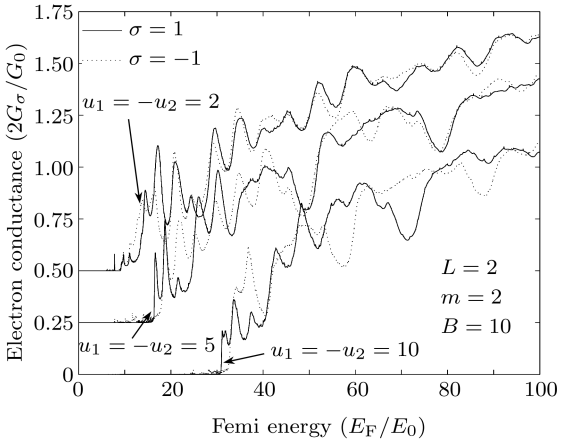


Fig.6. The conductance of electron as a function of Fermi energy for the different electric barriers. For clarity, curves corresponding to $u_1 = -u_2 = 2$ and 5 are offset by 0.5 unit and 0.25 unit of $2G_\sigma/G_0$ respectively.

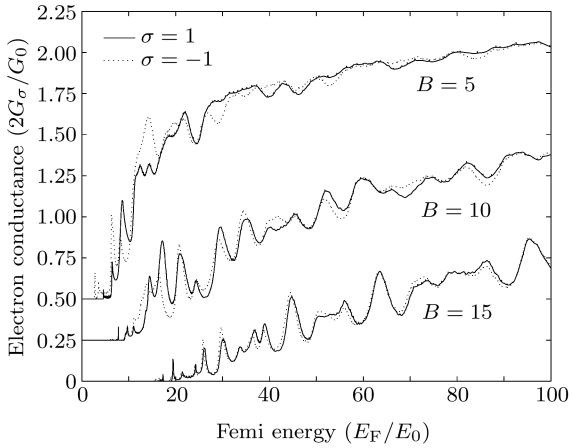


Fig.7. The conductance of electron versus the Fermi energy for the different magnetic fields. Curves corresponding to $B = 5$ and 10 are offset by 0.5 unit and 0.25 unit of $2G_\sigma/G_0$ respectively.

4. Summary and conclusion

In this paper, we detailedly investigate the electron transport characters in the 2DEG with the periodic magnetic-electric barriers, and find that they are strongly affected not only by the incident electron energy, the incident wave vector and the magnetic-electric barriers, but also by the number of the periodic magnetic-electric barriers. A noticeable feature is that the transmission coefficient and the spin polarization exhibit a periodic pattern with the increase of L. As the number of the periodic magnetic-electric barriers increases, the resonance splitting increases, and a polarization can be achieved by spin-dependent resonant tunnelling in this structure, although the average magnetic field of the structure is zero.

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