Giant magnetoresistance effect of two-dimensional electron gas systems in a periodically modulated magnetic field

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We investigated a giant magnetoresistance (MR) effect of two-dimensional electron gas systems subjected to a periodically modulated magnetic field. It is found that the MR ratio of such a periodically modulated system shows strong dependence on the space between the magnetic potentials. With the increase in the number of periods, the maximal MR ratio tends to be enhanced and the peak of the MR ratio locates at a specific relative Fermi energy for the given space between magnetic potentials. Moreover, the maximal MR ratio of odd-period configurations is always larger than that of even-period configurations.

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I. INTRODUCTION

Because of many fascinating practical applications, a large magnetoresistance (MR) effect has been searched for during the past several decades. In particular, a breakthrough came with the discovery of the giant magnetoresistance (GMR) in magnetic multilayers,[1] and also in heterogeneous CuCo granular alloys.[2] In general, spin-dependent scattering from the interface and the bulk is proposed as the source of GMR.[3] Moreover, colossal magnetoresistance (CMR) in manganese perovskites with MR ratio over 10^5% at low temperature has been observed,[4] which has a completely different physical origin from the GMR effect in layered and clustered compounds.[5] Recently, ballistic magnetoresistance (BMR) in ferromagnetic nanocontacts was studied,[6] and 10^5% BMR in stable Ni nanocontacts at room temperature was observed recently.[7]

To obtain a large MR ratio, an attractive alternative approach is to use the magnetic or superconducting microstructure on the surface of heterostructures with a two-dimensional electron gas (2DEG) providing an inhomogeneous magnetic field that influences locally the motion of the electrons in the semiconductor. Nogaret *et al.* demonstrated a MR effect in hybrid ferromagnetic and/or semiconductor devices at low temperature,[8] and a MR ratio of up to 10^3% at 4 K has been observed recently.[9] It was also reported that MR oscillations, due to the internal Landau band structure of a 2DEG system, can be observed in a periodic magnetic field.[10] Theoretical developments have focused on the energy spectrum and transport properties,[11] such as wave-vector filtering,[12] energy spectrum, and resonant splitting,[13,14] as well as MR[15] of a 2DEG in weakly modulated magnetic fields, in the ballistic regime and in the diffusive limit.[16]

Very recently, another interesting MR effect was demonstrated in a magnetically modulated 2DEG system,[17] where the configuration consisting of four delta magnetic potentials was considered. Compared with previous works, this kind of system features very high MR ratio even though the average magnetic field is zero. One may wonder about a periodic magnetic superlattice consisting of the above configurations. It is well known that superlattices possess many interesting electronic transport properties and band structures. The dispersion in the vertical direction is determined by the artificial periodicity and the coupling among successive quantum wells rather than by the properties of the individual semiconductor layer.[18] So we expect that a 2DEG system modulated by the periodic magnetic potentials may be a promising candidate to achieve new magnetic-electronic devices. In this paper, we investigate the MR effect of a 2DEG system modulated by the periodic magnetic potentials with the Laudauer-Büttiker theory. The MR effect shows distinct features compared to previous works[17] with a change in the magnetic structure parameters of this system. Furthermore, the different characteristic of odd-period and even-period configurations has been found.

II. MODEL AND FORMULAS

The magnetic potential considered here is chosen to be the magnetic Kronig-Penney superlattice (MKP),[13,19] which is the analogy of the well-known electrostatic Kronig-Penney model and is also perpendicular to the 2DEG in the (x,y) plane, i.e., $B(x)/B_0=\gamma\sum_{n=-\infty}^{n=+\infty}\{[\delta(x+1+nL)-\delta(x+2+nL)]+\lambda[\delta(x+2+w+nL)-\delta(x+L+nL)]\}$. For such a magnetic field, the vector potential takes the form $\vec{A}(x)=(\mathbf{0},A(x),\mathbf{0})$ according to the Landau gauge. The potentials can be altered from an antiparallel (AP) configuration to one that is parallel (P). This system, with P and AP configurations for two periods, is depicted in Fig. 1 together with the corresponding vector potential profiles, where L is the length of a period, W is the space between magnetic potentials, γ is a parameter characterizing the magnetic field strength, and λ represents the magnetization configuration (±1 or P/AP).

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

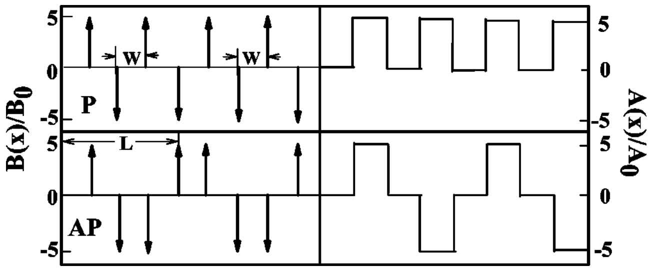

FIG. 1. The proposed magnetic field profiles together with the corresponding vector potential for the parallel (P) and antiparallel (AP) configurations. For simplicity, only two periods are plotted.

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

where m^* is the effective mass of electron, m_0 is the free-electron mass in vacuum, e is the absolute value of the electron's charge, $\vec{p}$ is the momentum operator, $\sigma=+1/-1$ for the up- and/or down-spin electron, and g^* is the effective g factor of the electron. The last term in Eq. (1) represents the Zeeman coupling between the electronic spin and the local magnetic field.[20] Since $[p_y,H]=0$, the system is a translational invariant along the y direction. Then the wave functions can be written as $\psi(x,y)=1/(\sqrt{l_y})e^{ik_y y}\psi(x)$, where k_y is the wave vector and l_y is the structure length in the y direction. By introducing the magnetic length $l_B=\sqrt{\hbar/eB_0}$ and the cyclotron frequency $\omega_c=eB_0/m^*$, all the physical quantities can be expressed in the dimensionless units: (i) the coordinate $\vec{r}\to\vec{r}l_B$, (ii) the magnetic field $\vec{B}_z(x)\to\vec{B}_z(x)B_0$, (iii) the vector potential $\vec{A}(x)\to\vec{A}(x)B_0 l_B$, and (iv) the energy $E\to E\hbar\omega_c$.[12] In our calculation, we take $B_0=0.1$ T, and this leads to the units $l_B=813$ Å, $E_0=\hbar\omega_c=0.17$ meV for GaAs system with $m^*=0.067\,m_0$ and $g^*=0.44$. The following 1D Schrödinger equation for $\psi(x)$ can be obtained:

$$\left\{\frac{d^2}{dx^2} - [k_y + A(x)]^2 - \frac{g^* m^* \sigma B_z(x)}{2m_0} + 2E\right\}\psi(x) = 0. \tag{2}$$

By defining $k^2=2E-[k_y+A(x)]^2-g^*m^*\sigma B_z(x)/2m_0$, Eq. (2) can be reduced to

$$\left(\frac{d^2}{dx^2} + k^2\right)\psi(x) = 0. \tag{3}$$

It is useful to introduce the effective potential $U_{eff}(x,k_y)=E-k^2/2$ of the magnetic potentials. the effective potential depends strongly not only on the longitudinal wave vector k_y, but also on the profile of magnetic potentials. When the P configurations turn to the AP configurations, U_{eff} varies substantially. It is the dependence on the magnetic profile of U_{eff} that leads to the MR effect in the involving systems.

We suppose that the magnetic modulation is restricted in region $[0,L]$ and the magnetic potential is zero at $x<0$ or $x>L$. If we divide the region into $N(N\geqslant 1)$ segments, the modulation potential could be considered as constant in each part. Thus, the plane wave function can be expressed as

$$\psi(x) = \begin{cases} c_- e^{ik_- x} + \overline{c_-} e^{-ik_- x}, & x < 0, \\ c_j e^{ik_j(x-jd)} + \overline{c_j} e^{-k_j(x-jd)} (j=1,2,\ldots,N), & 0 \leqslant x \leqslant L, \\ c_+ e^{ik_+(x-L)} + \overline{c_+} e^{-ik_+(x-L)}, & x > L, \end{cases} \tag{4}$$

where $k_-=k_+=\sqrt{2E-k_y^2}$, $k_j=\sqrt{2E-[k_y+A(x_j)]^2-g^*m^*\sigma B_z(x_j)/2m_0}(x_j=jd)$. According to the continuity of the wave functions and their derivatives at $x=0$, $x_j=jd$, and $x=L$, one can derive

$$\begin{pmatrix} c_+ + \overline{c_+} \\ c_+ - \overline{c_+} \end{pmatrix} = \begin{pmatrix} \cos(k_N d) & i\sin(k_N d) \\ \frac{ik_N}{k_+}\sin(k_N d) & \frac{k_N}{k_+}\cos(k_N d) \end{pmatrix} \times \prod_{j=1}^{N-1} M(j) \times \begin{pmatrix} \cos(k_- d) & i\sin(k_- d) \\ \frac{ik_-}{k_1}\sin(k_- d) & \frac{k_-}{k_1}\cos(k_- d) \end{pmatrix} \begin{pmatrix} c_- + \overline{c_-} \\ c_- - \overline{c_-} \end{pmatrix}, \tag{5}$$

where

$$M(j) = \begin{pmatrix} \cos(k_j d) & i\sin(k_j d) \\ ik_j/k_j + 1\,\sin(k_j d) & k_j/k_{j+1}\cos(k_j d) \end{pmatrix}.$$

Equation (5) can be reduced to a simpler form

$$\begin{pmatrix} c_+ + \overline{c_+} \\ c_+ - \overline{c_+} \end{pmatrix} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} \begin{pmatrix} c_- + \overline{c_-} \\ c_- - \overline{c_-} \end{pmatrix}. \tag{6}$$

In the region $x>L$, there exists only transmission waves, i.e., $\overline{c_+}=0$. Thus, we obtain

$$\frac{\overline{c_-}}{c_-} = \frac{m_{11}+m_{12}-m_{21}-m_{22}}{m_{21}+m_{12}-m_{11}-m_{22}}. \tag{7}$$

The transmission coefficient is given by[21]

$$T = R = 1 - \left|\frac{\overline{c_-}}{c_-}\right|^2 = 1 - \left|\frac{m_{11}+m_{12}-m_{21}-m_{22}}{m_{12}+m_{21}-m_{11}-m_{22}}\right|^2. \tag{8}$$

Furthermore, we can calculate the ballistic conductance at zero temperature from the Laudauer-Büttiker formula[22]

$$G = G_0\int_{-\pi/2}^{\pi/2} T(E_F, \sqrt{2E_F}\sin\theta)\cos\theta\, d\theta, \tag{9}$$

where θ is the angle between the incident direction and the x axis, $G_0=2e^2m^*v_F l_y/\hbar^2, E_F$, is the Fermi energy, and v_F is the Fermi velocity of electrons.

MR ratio usually has two definitions, i.e., $MR=(G_P-G_{AP})/G_{AP}$ and $MR=(G_P-G_{AP})/G_P$, where G_P and G_{AP} are the conductance for the parallel and antiparallel alignments, respectively. Obviously, the MR ratio calculated by the different definitions is distinct for some cases. In order to compare with the previous theoretical works,[17] here we adopt the definition of the MR ratio by $MR=(G_P-G_{AP})/G_{AP}$.

Although the delta function $B_z(x)$ is locally infinite, the effect of the polarization $g^*m^*B_z(x)/m_0$ on the MR will extend to the whole infinite space

$$\Delta MR \propto \int_0^\infty \frac{g^* m^* B_z(x)}{m_0} dx \propto \frac{g^* m^* B}{m_0}. \qquad (10)$$

It is evident that the effect of the Zeeman Effect on the MR is closely rested on the $g^* m^*/m_0$. Comparing to other terms in U_{eff}, the absolute value of such Zeeman term is much smaller (the comparison between them is estimated as $g^* m^*/4m_0 = 0.0074 \ll 1$). Therefore, the spin-dependent term plays a minor role in determining the transport properties of electrons[23] and can be omitted for the present GaAs system.

III. RESULTS AND DISCUSSION

First of all, we studied the MR effect of 2DEG for one period with the magnetic field $B=5$ and different space of potentials W. Figures 2(a)–2(e) present the MR ratio as a function of the Fermi energy for different W: (a) $W=1$, (b) $W=2$, (c) $W=3$, (d) $W=4$, and (e) $W=5$. It is obvious that the MR ratio shows drastic oscillations with the increase of the Fermi energy, the MR effect mainly occurs in the low Fermi energy region, and the MR ratio almost reduces to zero for the large Fermi energy. As W increases, the oscillation of the MR ratio is enhanced and the value of the maximal MR ratio is reduced rapidly. To see it more clearly, Fig. 3 displays the maximal MR ratio for different W. There is a quasilinear relationship between the maximal MR ratio and W. It can be believed that these phenomena result from the variation of another measurable quantity, the conductance G. In the inset of Fig. 2, we present the conductance G_P (dashed curve) and G_{AP} (solid curve) for the P and AP configurations versus the Fermi energy for different W. Within the low-energy region, the conductance is almost zero for both P and AP configurations. Beyond this region, G_P is enhanced significantly with the increase of the Fermi energy. Furthermore, there exists a wide region of the Fermi energy where G_{AP} is almost closed to zero whereas G_P is finite. It is this large suppression of the conductance of the AP configurations that results in a large MR effect.

As is well known, for electron tunneling through the electric superlattice, when the Fermi energy of electrons coincides with the energy of bound states in the potential well, resonant tunneling occurs and the transmission coefficient reaches unity. Although electron tunneling in the magnetic superlattice is more complicated than that in the electronic superlattice due to its dependence on the perpendicular wave vector,[12] the problem can be reduced to one dimensional when we introduce the effective potential. Hence, electron tunneling in the magnetic superlattice is similar to that in the electronic superlattice for a given wave vector, from the mathematical viewpoint. Because of the coupling between the wells via tunneling through the barriers of finite width, the degenerated eigenlevels of the independent well are split. Consequently, these split levels redistribute themselves into groups around their unperturbed positions and form quasibands. This leads to the resonant splitting of the transmission and oscillations of the MR ratio of the magnetic superlattice as mentioned above.

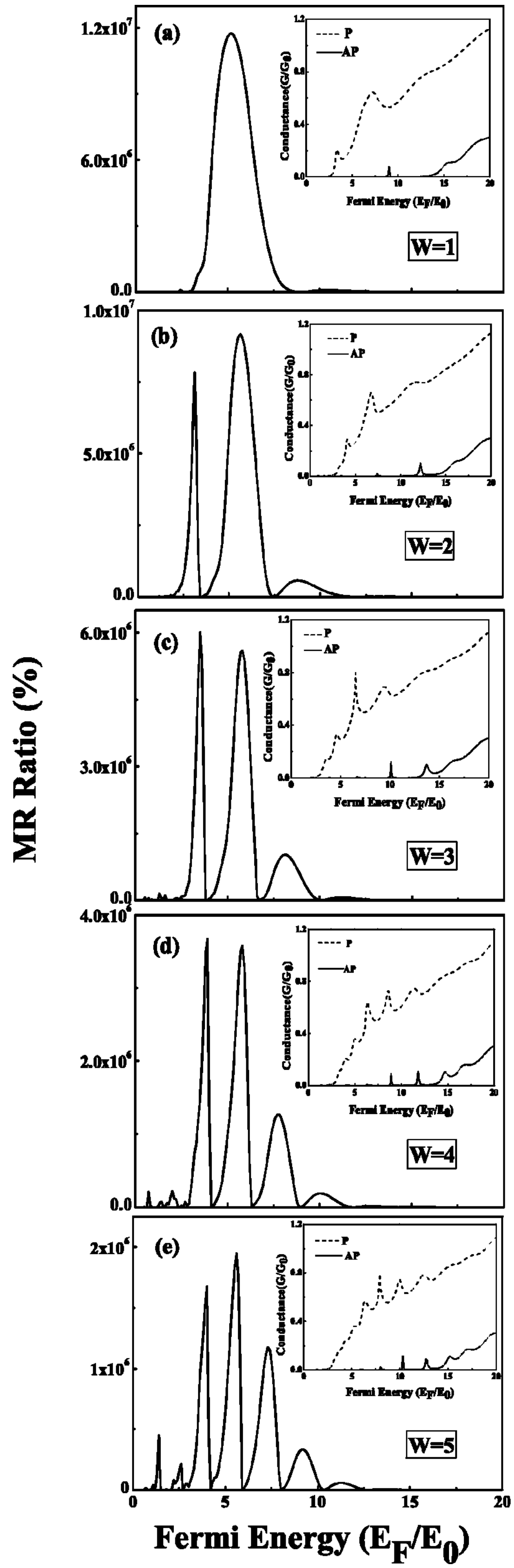

FIG. 2. The magnetoresistance (MR) ratio vs. the Fermi energy for different space of potentials W. (a) $W=1$, (b) $W=2$, (c) $W=3$, (d) $W=4$, (e)$W=5$. The magnetic structure parameter is $B=5.0$. The insets show corresponding conductance of electrons as a function of the Fermi energy for both P (dashed curve) and AP (solid curve) configurations.

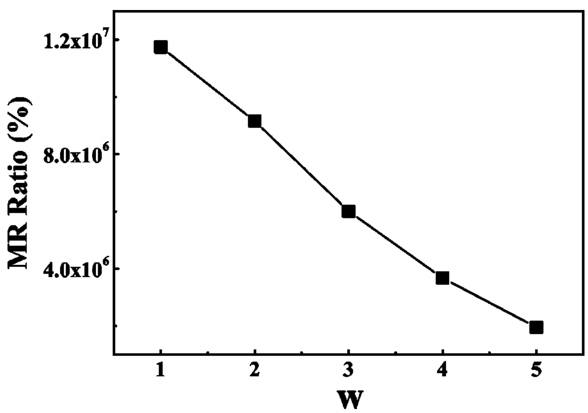

FIG. 3. The maximal MR ratio versus space of potentials W from 1 to 5. Other structure parameters are the same as those in Fig. 2.

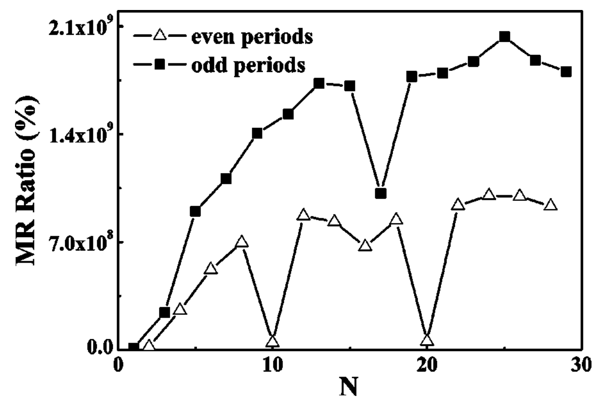

FIG. 5. The maximal MR ratio as a function of the number of periods for both OP(■) and EP(Δ) configurations. Structure parameters are the same as those in Fig. 4.

The specific W may result in the great difference of wave-vector-dependent transmission between two configurations (P/AP) at a specific incident electron energy, although the conductance of both P and AP configurations have relatively abundant oscillations.

To study the MR effect of 2DEG modulated by the periodic magnetic potentials, Fig. 4 shows the numerical results of the MR ratio from 2 to 9 periods, where $W=1$ and other parameters of the magnetic structure are the same as those in Fig. 2. In considering that the MR ratio is almost zero in the high-Fermi energy, the range of the Fermi energy is taken from 0 to 8 in the unit of E_0. It is obvious that there is only one peak for different periods, and position of peak locates at $3.41E_F/E_0$. This is an interesting result compared to the previous results,[17] where more complicated MR ratio oscillations exist. It indicates that electrons with the relative Fermi energy $E_F=3.41E_0$ are more sensitive to the magnetic field in the given structure. From an applications point of view, this kind of magnetic structure is advantageous for the selective electron injection devices.

In Fig. 5 we present the maximal MR ratio versus the number of periods with the same parameters given in Fig. 4; the number of periods are chosen from 1 to 29. As the number of periods increases, the MR ratio shows oscillations and tends to be enhanced. More interestingly, the maximal MR ratio of odd-period (OP) configurations is always larger than that of even-period (EP) configurations,which could be attributed to the discrepancy of the effective potentials between OP and EP configurations with the increase of periods. Since the ballistic conductance is derived as the transmission averaged over all the possible wave vectors, it can be viewed as the transmission of the electron's collective tunneling with a characteristic wave vector through an average effective potential, which has the same number of barriers as the magnetic vector potential. This can be seen clearly if we plot the effective potential as a function of x coordination and wave vector as done by Ibrahim and Peeters.[13] Hence, we could analyze the change in the magnetic vector potential to study the influence of the corresponding effective potential. For AP configurations, the number of magnetic vector potential wells in OP configurations are equal to the number of the equiform magnetic vector potential barriers in the adjacent EP with the increase of periods. This change leads to the corresponding difference of effective potentials between OP and EP configurations.

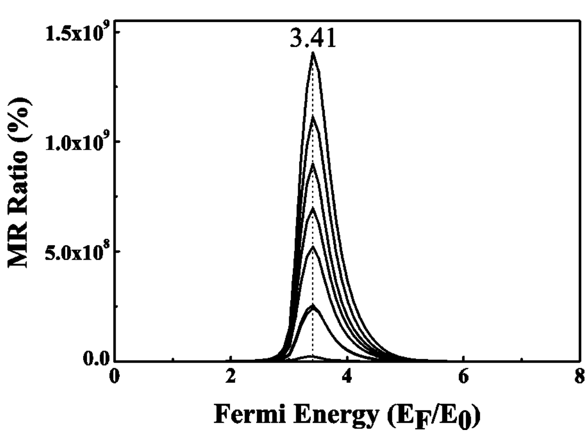

FIG. 4. The MR ratio vs the Fermi energy from two to nine periods for $W=1$. Other structure parameters are the same as those in Fig. 2.

All results presented so far are obtained for the zero temperature case. For finite temperatures, the main contribution to the ballistic conductance comes from electrons located in the region (E_F-k_BT, E_F+k_BT). The uncertainty of the wave vector is thus $\Delta k=(k_BT/E_F)k_F$, where k_F is the Fermi wave vector. With the increase in temperature, the coherence from different interfaces will lose when $\Delta k\times L>\pi$. For very low temperatures, resonant tunneling still exists for the considered magnetic structures.

IV. CONCLUSIONS

We have investigated the MR effect in magnetically modulated 2DEG systems. The results show that the MR ratio is greatly influenced by the space between the magnetic potentials and the number of periods, and the larger MR ratio can also be achieved by properly modulating the parameters of the magnetic structures. With the increase in the number of periods, the maximal MR ratio tends to be enhanced and the peak of the MR ratio locates at a specific relative Fermi energy for $W=1$. Moreover, it is suggested that the discrepancy of the effective potentials leads to the larger maximal MR ratio of odd period configurations than that of even period ones. Sequentially, the present study implies that a magnetically modulated 2DEG system may be an ideal candidate for magnetic-electronic devices.

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