# Giant magnetoresistance in a two-dimensional electron gas modulated by ferromagnetic and Schottky metal stripes*

Lu Jianduo(卢建夺)[1,†] and Xu Bin(徐宾)[2]

[1]Hubei Province Key Laboratory of Systems Science in Metallurgical Process, Wuhan University of Science and Technology, Wuhan 430081, China

[2]Department of Mathematics and Information Sciences, North China Institute of Water Conservancy and Hydroelectric Power, Zhengzhou 450011, China

**Abstract:** In this paper, by using the transfer matrix method, we theoretically investigate the magnetoresistance (MR) effect in a two-dimensional electron gas (2DEG) modulated by two Schottky metal (SM) stripes and two ferromagnetic (FM) stripes on the top and bottom of the 2DEG. From the numerical results, we find that a considerable MR effect can be achieved in this device due to the significant difference between electron transmissions through the parallel and antiparallel magnetization configurations. We also find that the MR ratio obviously depends on the magnetic strength and the electric-barrier height as well as the distance between the FM and SM stripes. These characters are very helpful for making the new type of MR devices according to their practical applications.

**Key words:** magnetic nanostructure; magnetoresistance effect; magnetoresistance ratio

**DOI:** 10.1088/1674-4926/32/7/074007 **EEACC:** 5180; 2560X; 3120

## 1. Introduction

In recent years, the discovery of the so-called giant magnetoresistance (MR) effect[1] has given rise to a tremendous economic impact on magnetic information storage[2, 3], such as read heads, random access memories and ultra-sensitive magnetic field sensors. Motivated by these fascinating practical applications, the giant MR effect has attracted numerous theoretical and experimental studies[4−6]. Generally, the MR effect can be observed in the structures consisting of two ferromagnetic (FM) layers separated by a thin nonmagnetic layer. In such structures, the MR is characterized by a striking drop of the electric resistance when an external magnetic field switches the magnetizations of adjacent magnetic layers from a parallel (P) alignment to an antiparallel (AP) one.

For a practical MR device, one expects to have the high MR ratio under a relatively low switching magnetic field. An alternative way[7−10] to obtain a large MR ratio is to use a two-dimensional electron gas (2DEG) modulated by nanosized FM stripes providing an in-homogeneous magnetic field which can locally influence the motion of the electron in the semiconductor. In this kind of nanosystem, it is found that the electron-spin effect plays a minor role on the giant MR effect and so can be ignored, and the MR ratio of the device is very high[11−16]. Although many studies have been directed on the giant MR effect for magnetic-barrier nanosystems, to the best of our knowledge, the study of the giant MR effect in the device as shown in Fig. 1(a) is still an open question.

Therefore, in the present work, we theoretically study the giant MR effect in a 2DEG modulated by two Schottky metal (SM) stripes, and two FM stripes on the top and bottom of the 2DEG, although Lu *et al*[17,18] and Liu *et al*[19] have investigated a giant MR device which can be realized by the deposition of an SM stripe, and two parallel FM stripes on the top of a GaAs heterostructure. Our numerical results not only show that there exists a considerable MR effect due to the remarkable discrepancy in electronic transmissions through the P and AP configurations of the ferromagnetic layers, but also show that the MR ratio is obviously affected by the magnetic strength and the electric-barrier height as well as the distance between the FM and SM stripes.

## 2. Theoretical method and formulas

Our proposed MR device is a 2DEG modulated by two SM stripes, and two FM stripes as schematically depicted in Fig. 1(a), which can be experimentally realized by modern nanotechnology[20−22], For simplicity, the electric barriers and the magnetic field can be approximated as squares ($U_1$ and $U_2$) and a delta function[8], respectively, as shown in Figs. 1(b) and 1(c) corresponding to the P and AP configurations of two FM layers, respectively. The magnetic field can be expressed as $\boldsymbol{B} = B_z(x)\boldsymbol{z}$ with $B_z(x) = B_1\delta(x-a-b) - \lambda B_2\delta(x-a-b-c)$, where $B_1$ and $B_2$ give the strengths of the magnetic fields, $a$ and $c$ denote the width of the SM stripes and the space between the two magnetic fields, respectively, $b$ and $d$ are separations between the adjacent electric barrier and magnetic field, and $\lambda$ represents the magnetization configuration. The symbol $\lambda = 1(-1)$ is for P(AP) configuration.

Assume that the magnetic field and the electric potential are homogeneous in the $y$-direction and only vary along the $x$ axis. The motion of an electron in such a modulated 2DEG sys-

* Project supported by Hubei Province Key Laboratory of Systems Science in Metallurgical Process, Wuhan University of Science and Technology (No. C201018).

† Corresponding author. Email: l_j316@163.com

Received 15 December 2011, revised manuscript received 13 February 2012 

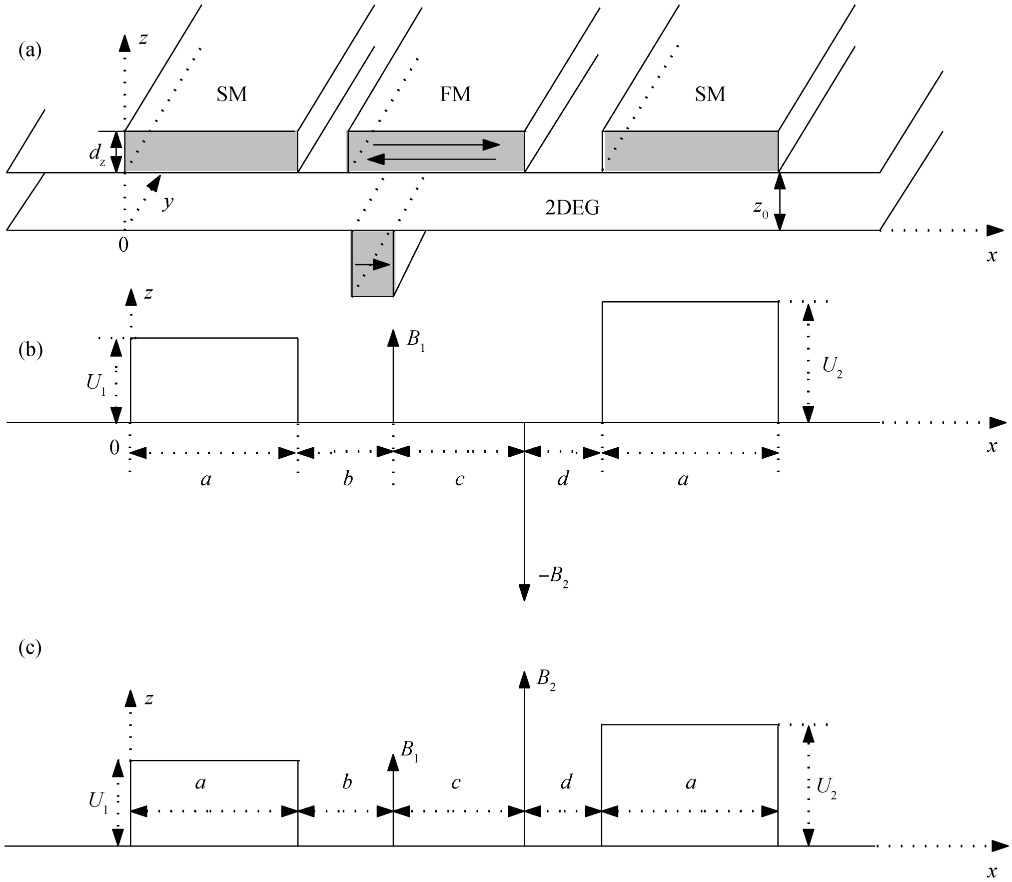


Fig. 1. (a) Schematic illustration of the MR device, where two SM stripes are placed on the top of the 2DEG, and two FM stripes are placed on the top and bottom of the 2DEG. Theoretical models for the magnetic field and electric potential profiles for the (b) P and (c) AP configurations of the two FM stripes. Here, we choose the parameters: $a = b = c = 1$, $B_1 = 1$ and $U_1 = 1$.

tem in the $(x, y)$ plane can be described by the single-particle Hamiltonian

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

where $\boldsymbol{p}$ is the momentum of the electron, $\boldsymbol{A}(x) = [0, A(x), 0]$ is the magnetic vector potential given in the Landau gauge, $m^*$ and $m_0$ are the real and the effective masses of the electron, $\sigma = +1/-1$ for spin-up/down electrons, and $g^*$ is the effective Landé factor. For simplicity, we introduce the dimensionless units, the electron cyclonic frequency $\omega_c = eB_0/m^*$ and the magnetic length $l_{B_0} = \sqrt{\hbar/eB_0}$ 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 electric barrier $U_{1/2} \to \frac{\hbar\omega_c}{e}U_{1/2}$, (3) the coordinate $\boldsymbol{r} \to l_{B_0}\boldsymbol{r}$, (4) the vector potential $\boldsymbol{A}(x) \to B_0 l_{B_0}\boldsymbol{A}(x)$, and (5) the magnetic field $\boldsymbol{B}_z(x) \to B_0\boldsymbol{B}_z(x)$. For GaAs and an estimated $B_0 = 0.1\ T$, we have $l_{B_0} = 813$ Å, $\hbar\omega_c = 0.17$ meV, and $g^* = 0.44$.

Because of the translational invariance of the system along the $y$-direction, the total electronic wave-function can be written as $\Psi_l(x, y) = \mathrm{e}^{ik_y y}(\mathrm{e}^{ik_l x} + \gamma\mathrm{e}^{-ik_l x})$, $x < 0$ and $\Psi_r(x, y) = \tau\mathrm{e}^{ik_y y}\mathrm{e}^{ik_r x}$, $x > 2a + b + c + d$, where $k_l = \sqrt{2E - k_y^2}$, $k_r = \sqrt{2E - (k_y + B_1 - \lambda B_2)^2}$, the symbol $k_y$ stands for the longitudinal wave vector of the electron, and $\gamma/\tau$ denotes the reflection/transmission amplitude. Therefore, using the transfer matrix method, one can obtain the transmission coefficient as $T_\lambda(E, k_y) = \frac{k_r}{k_l}|\tau|^2$.

When the electron transmission coefficient is obtained, the ballistic conductance at zero temperature can be calculated from the well-known Landauer–Buttiker formula[23]:

$$G_\lambda(E_\mathrm{F}) = G_0\int_{-\pi/2}^{\pi/2} T_\lambda(E_\mathrm{F}, \sqrt{2E_\mathrm{F}}\sin\phi)\cos\phi \mathrm{d}\phi, \qquad (2)$$

where $G_0 = 2e^2 m^* \upsilon_F L_y/h^2$, $E_\mathrm{F}$ is the Fermi energy, $\upsilon_\mathrm{F}$ is the velocity corresponding to $E_\mathrm{F}$, $L_y$ is the length of the barrier structure in the $y$-direction, and $\phi$ is the angle of incidence relative to the $x$-direction.

For an MR device, its MR ratio could be defined as MRR $= (G_\mathrm{P} - G_\mathrm{AP})/G_\mathrm{P}$ and MMRR $= (G_\mathrm{P} - G_\mathrm{AP})/(G_\mathrm{P} + G_\mathrm{AP})$, where $G_\mathrm{P}$ and $G_\mathrm{AP}$ are the conductances for the P and AP alignments, respectively. Obviously, the MR ratio calculated by the different definitions is distinct for some cases. In this work, we adopt the MMRR definition to study the MR effect. As the electronic spin and the local magnetic field interaction depends on the quantity $g^* Bm^*/2m_0$, and even for $B = 5$ the value of such a quantity is 0.0737 for GaAs, which is much smaller than $E_\mathrm{F}/E_0$, therefore we will neglect the spin-dependent part in the subsequent discussion.

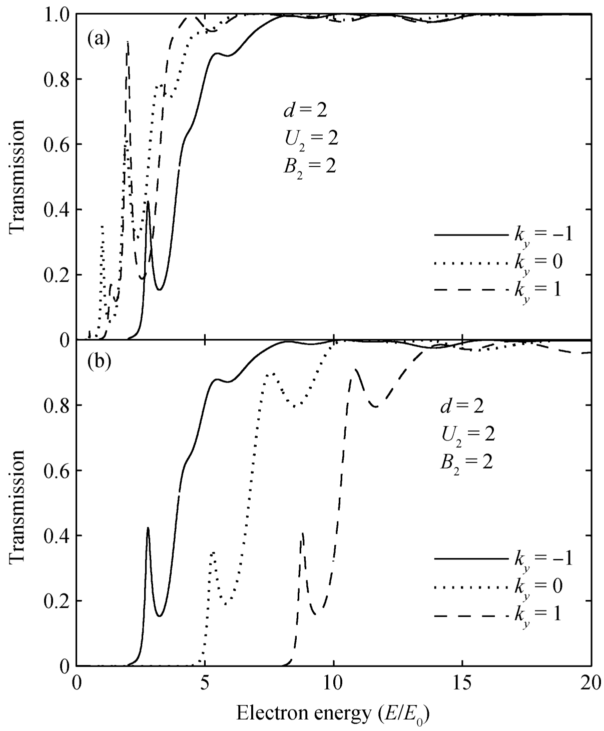


Fig. 2. Transmission coefficients for electrons tunneling through the (a) P and (b) AP configurations.

## 3. Numerical results and discussion

First of all, we plot Figs. 2(a) and 2(b) to present the transmission coefficients for electrons tunneling through the P and AP configurations, respectively. Apparently, a remarkable discrepancy occurs in the transmission for electrons through the P and AP configurations of the FM stripes. For the P configuration, it can be clearly seen that there are several incomplete resonant peaks in the low-energy region. However, when the system switches from the P configuration to the AP configuration, it can be obviously seen that the electron transmission is greatly altered. The transmission curves evidently shift to the higher energy and are significantly suppressed in contrast to the P configuration as well as the low-energy resonant peaks almost disappearing.

Having seen the configuration-dependent transmission features, one may expect to know what extent such a difference is reflected in measurable quantities, which often involves some kind of averaging. Therefore, in Fig. 3, we present the conductances for electrons tunneling through the P and AP alignments corresponding to Figs. 3(a) and 3(b), respectively. From the two figures, one can clearly see that there exists a large suppression of the conductance $G_{\mathrm{AP}}$, especially in the low Fermi energy region, due to the great reduction of the electron tunneling through the AP alignment, in contrast to the P configuration. With the increase of the magnetic strength, $B_2$, the conductance greatly decreases, which tells us that the magnetic strength significantly suppresses the conductance. With the increase of the Fermi energy, the conductance oscillatorily increases and has the smaller oscillatory magnitude. These characters can be seen more clearly from the MMRR curves as shown in Fig. 3(c). A considerable MR effect can be evidently

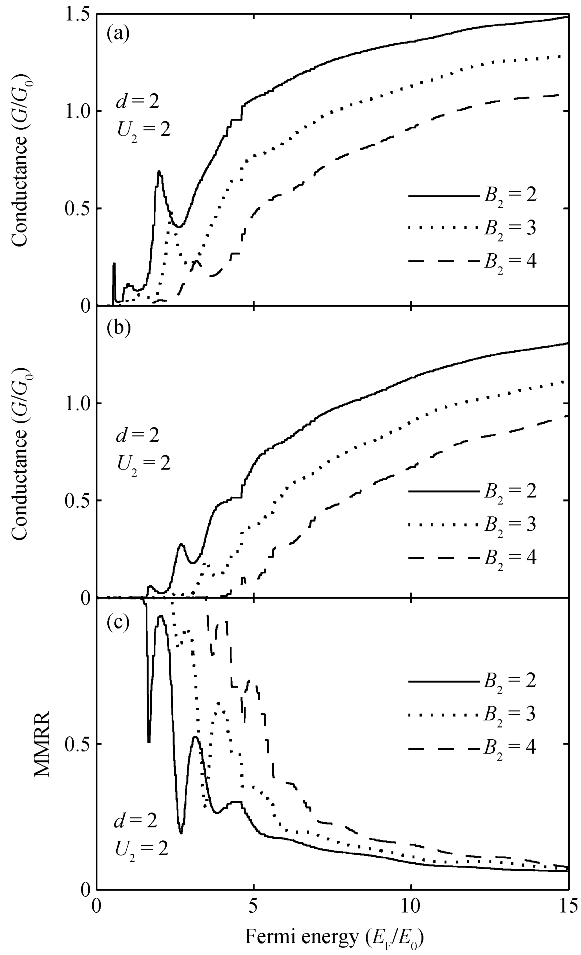


Fig. 3. Electron conductances for the (a) P and (b) AP alignments, respectively. The MR ratio as a function of Fermi energy is given in (c) for the same parameters.

seen due to the large suppression on the conductance of the AP alignment. In the low-energy region, the MMRR can be up to 100%, and with the increase of the Fermi energy the MMRR oscillatorily decreases. Moreover, the MMRR curve strikingly shifts rightwards with increasing the magnetic strength.

Next, in order to display the influence of the electric barrier on the MR effect, we give the conductances for electrons tunneling through the P and AP configurations corresponding to Figs. 4(a) and 4(b), respectively. Once again, one can find that there is a large suppression on the conductance of the AP alignment, due to the great reduction of the electron tunneling through the AP alignment, in contrast to the P configuration. With increasing the electric-barrier height, the conductances for both P and AP configurations greatly decrease, in other words, the electric barrier significantly suppresses the conductances. In Fig. 4(c), the MR ratio MMRR of the device is shown for the different heights of the electric barrier. From this figure, we can easily see that with the increase of the electric-barrier height, the MMRR greatly increases and the resonant peaks of the MMRR obviously shift to the higher Fermi energy. We also can find that by increasing the Fermi energy, the MMRR oscillatorily decreases and it has the smaller oscillatory magnitude.

Finally, we examine the influence of the distance between the SM and FM stripes on the MR effect of the device as plotted

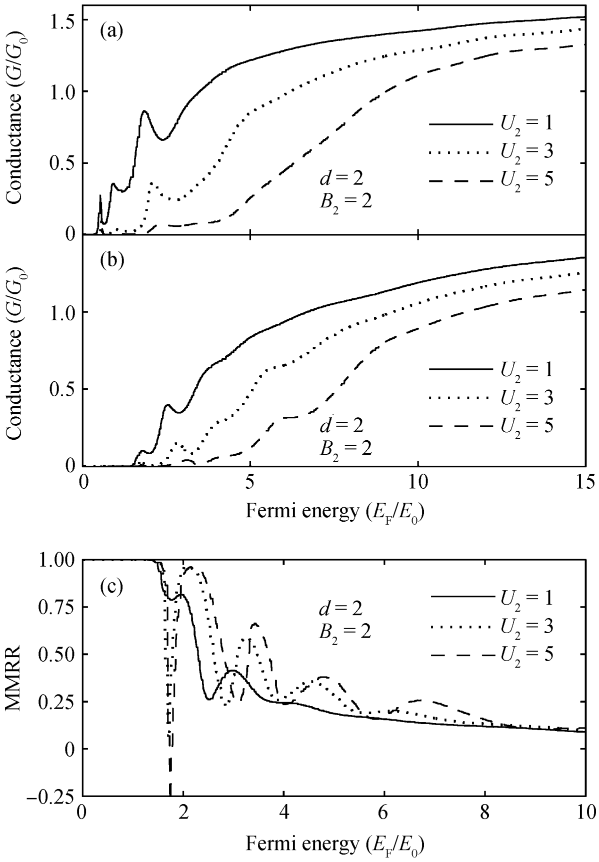


Fig. 4. Conductances for electrons tunneling through the (a) P and (b) AP configurations, respectively. (c) MR ratio as a function of Fermi energy for the same parameters.

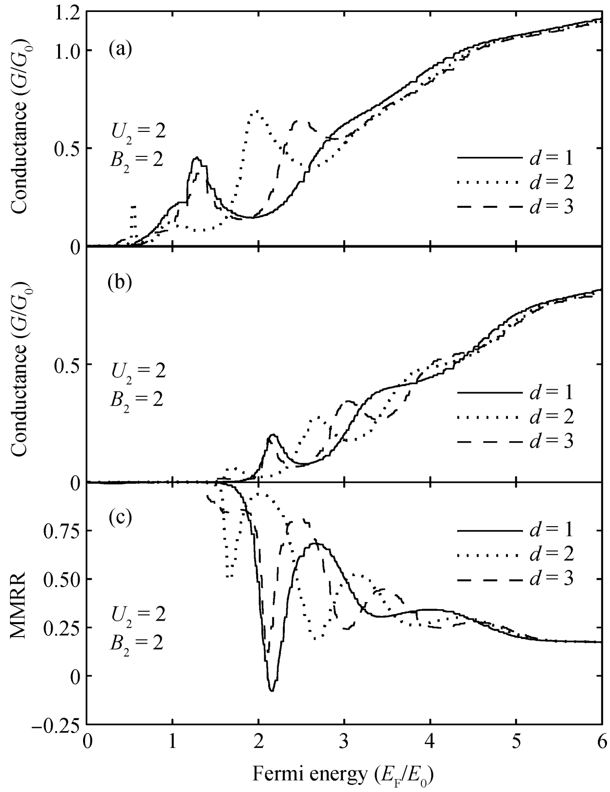


Fig. 5. Electron conductances for the (a) P and (b) AP alignments, respectively. The MR ratio as a function of Fermi energy is given in (c) for the same parameters.

in Fig. 5, where Figures 5(a) and 5(b) correspond to the P and AP configurations, respectively, and Figure 5(c) shows the MR ratio as a function of Fermi energy for the same parameters. From the figure, it can be easily found that the conductances for electrons tunneling through the P and AP alignments evidently depend on the distance $d$. Therefore, the MR ratio also greatly depends on the distance. Moreover, for the distance $d = 1$, the oscillatory magnitude of the MMRR is much bigger than that for $d = 2$ or $d = 3$. Therefore, one can control the MR effect by changing the distance between the SM and FM stripes.

## 4. Conclusion

In summary, we have theoretically studied the giant MR effect in a 2DEG modulated by the FM and SM stripes. It is found that a considerable MR effect can be achieved in this device due to the significant difference between electron transmissions through the P and AP magnetization configurations. It is also found that the MR ratio obviously depends on the magnetic strength and the electric-barrier height as well as the distance between the FM and SM stripes. These characters are very helpful for making new types of MR devices according to the practical applications.

## References

[1] Baibich M N, Broto J M, Fert A, et al. Giant magnetoresistance of (001)Fe/(001)Cr magnetic superlattices. Phys Rev Lett, 1988, 61: 2472

[2] Prinz G A. Magnetoelectronics. Science, 1998, 282: 1660

[3] Wolf S A, Awschalom D D, Bubrman R A, et al. Spintronics: A spin-based electronics vision for the future. Science, 2001, 294: 1488

[4] Ansermet J P. Perpendicular transport of spin-polarized electrons through magnetic nanostructures. J Phys: Condens Matter, 1998, 10: 6027

[5] Gijs M A M, Bauer G E W. Perpendicular giant magnetoresistance of magnetic multilayers. Adv Phys, 1997, 46: 285

[6] Levy P M. Giant magnetoresistance in magnetic layered and granular materials. Solid State Phys, 1994, 47: 367

[7] Yang X D, Wang R Z, Guo Y, et al. Giant magnetoresistance effect of two-dimensional electron gas systems in a periodically modulated magnetic field. Phys Rev B, 2004, 70: 115303

[8] Papp G, Peeters F M. Giant magnetoresistance in a two-dimensional electron gas modulated by magnetic barriers. J Phys: Condens Matter, 2004, 16: 8275

[9] Papp G, Peeters F M. Tuneable giant magneto-resistance with magnetic barriers. J Appl Phys, 2006, 100: 043707

[10] Lu J D, Yi L. The bias- and temperature-dependent magnetoresistance effect in a magnetic nanostructure. Physica E, 2010, 43: 319

[11] Lu J D. The magnetoresistance effect in a nanostructure with the periodic magnetic barriers. Appl Surf Sci, 2008, 254: 3939

[12] Guo Y, Qin J H, Zhai F, et al. Wave-vector filtering and spin filtering in a magnetic double-barrier and double-well structure. Phys Lett A, 2004, 322: 117

[13] Zhai F, Guo Y, Gu B L. Giant magnetoresistance effect in a magnetic -electric barrier structure. Phys Rev B, 2002, 66: 125305

[14] Lu J D. Giant magnetoresistance effect in a magnetic barrier nanostructure. Superlattices and Microstructures, 2011, 49: 144
[15] Wang Y, Chen N F, Jiang Y, et al. Ballistic electron transport in hybrid ferromagnet/two-dimensional electron gas sandwich nanostructure: Spin polarization and magnetoresistance effect. J Appl Phys, 2009, 105: 013708
[16] Wang Y, Chen N F, Zhang X W, et al. Electric-tunable magnetoresistance effect in a two-dimensional electron gas modulated by hybrid magnetic-electric barrier nanostructure. Phys Lett A, 2009, 373: 1983
[17] Lu M W, Yang G J. Magnetoresistance effect in a both magnetically and electrically modulated nanostructure. Phys Lett A, 2007, 362: 489
[18] Lu M W, Zhang G L, Chen S Y. A GMR device based on hybrid ferromagnetic-Schottky-metal and semiconductor nanostructure. Semicond Sci Technol, 2008, 23: 035022
[19] Liu Y, Zhang L L. Giant magnetoresistance effect in hybrid ferromagnetic-Schottky-metal and semiconductor nanosystem. Phys Lett A, 2008, 372: 3729
[20] Kubrak V, Rahman F, Gallagher B L, et al. Magnetoresistance of a two-dimensional electron gas due to a single magnetic barrier and its use for nanomagnetometry. Appl Phys Lett, 1999, 74: 2507
[21] Vančura T, Ihn T, Broderick S, et al. Electron transport in a two-dimensional electron gas with magnetic barriers. Phys Rev B, 2000, 62: 5074
[22] Liu Y, Zhang L L. A magnetoresistance device based on a magnetic-barrier nanostructure. Semicond Sci Technol, 2008, 23: 075027
[23] Buttiker M. Four-terminal phase-coherent conductance. Phys Rev Lett, 1986, 57: 1761