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Giant magnetoresistance in a two-dimensional electron gas modulated by magnetic barriers and the δ-doping

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ABSTRACT

We theoretically investigate the modulation of the δ-doping to a semiconductor-based giant magnetoresistance (GMR) device, which can be realized experimentally by depositing two parallel ferromagnetic (FM) stripes on top and bottom of a GaAs/Al$_x$Ga$_{1-x}$As heterostructure. It is shown that a considerable GMR effect still exists in this device with the δ-doping. It is also shown that the magnetoresistance ratio (*MR*) depends on not only the weight but also the position of the δ-doping. These interesting results will be useful in understanding and designing structurally-controllable GMR devices for magnetic information storage.

1. Introduction

Recently, there are many theoretical and experimental works [1] dealing with the giant magnetoresistance (GMR) phenomenon [2], due to its fascinating practical applications in magnetic information storage such as ultrasensitive magnetic field sensors, read heads and random access memories [3]. GMR is generally observed in a structure consisting of ferromagnetic layers separated by thin non-magnetic layers. In such heterogeneous systems, GMR is characterized by a striking drop of the electric resistance when a external magnetic field switches the magnetization of adjacent magnetic layers from an antiparallel (AP) alignment to a parallel (P) one, i.e., the magnetoresistance ratio can be defined by [4] $MR = (G_P/G_{AP} - 1) \times 100\%$, where G_P and G_{AP} are the conductance for P and AP magnetization configurations, respectively. From the viewpoint of practical applications, a GMR device is expected to possess a large *MR* at a relatively small switching magnetic field.

To obtain a high *MR*, an attractive alternative is to use magnetic or superconducting nanostructures [5] on the surface of the semiconductor heterostructure containing a two-dimensional electron gas (2DEG), where nanosized ferromagnets or superconductors provide an inhomogeneous magnetic field influencing locally the motion of the electrons in the semiconductor. In a hybrid ferromagnetic/semiconductor device, Nogaret et al. [6] observed a *MR* of up to $10^3\%$ at 4 K. More recently, Zhai et al. [7] investigated the GMR effect in a magnetic nanostructure, which can be realized [8] experimentally by depositing two parallel ferromagnetic (FM) stripes on the top of the GaAs/Al$_x$Ga$_{1-x}$As heterostructure. Differing from the conventional metal-based GMR device, this kind of semiconductor-based GMR devices possesses a very high *MR* (up to $10^6\%$) for realistic electron densities and makes no use of the spin degree of freedom, which, therefore, will be ideal candidates for magnetic information storage. Several groups systematically explored the GMR effects in various kinds of magnetic nanostructures; see partial references [9–19].

Very recently, edified by an idea [20] to tailor the electronic transport via the δ-doping technique [21], how to structurally control semiconductor-based GMR devices in magnetic nanostructures has received much attention [22–25]. The semiconductor-based GMR devices are found to still have a considerable GMR effect when a δ-doping is comprised by the atomic layer doping. It is also found that the *MR* is closely related to the δ-doping, i.e., both magnitude and sign of the *MR* can be modified by adjusting the weight and/or position of the δ-doping in the GMR device. Motivated by these brief reports, in the present work we investigate theoretically the control to another GMR device based on a magnetic nanostructure to propose a structurally-manipulable GMR device for magnetic information storage.

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2. Model and theoretical method

As shown in Fig. 1(a), the semiconductor-based GMR device [11] can be experimentally realized [26] by depositing two nano-sized FM stripes with horizontal magnetizations on top and bottom of a GaAs/Al$_x$Ga$_{1-x}$As heterostructure, respectively. A suitable external magnetic field can switch the relatively orientation of two magnetizations of FM stripes from AP to P alignments, as indicated in Figs. 1(b) and 1(c), where the δ-doping $V\delta(x-x_0)$ with weight V and position x_0 can be introduced into the GMR device by the atomic layer doping technique [21]. For small distances between FM stripes and the 2DEG, the magnetic field profile induced by magnetized FM stripes can be approximated by delta functions, i.e., $B_z(x)=B\ell_B\{sgn(x)[\delta(|x|-w/2)\chi-\delta(|x|-d-w/2)]\}$, where B gives the strength of the magnetic field, $\ell_B=\sqrt{\hbar/eB_0}$ is the magnetic length for an estimated magnetic field B_0, $sgn(x)$ is the sign function, w and $(w+2d)$ are the width of bottom and top FM stripes respectively, and χ represents the magnetization configuration (±1 or P/AP). The Hamiltonian describing such a modulated 2DEG system in the (x,y) plane, in the single-particle effective-mass approximation, is

$$H=\frac{p_x^2}{2m^*}+\frac{[p_y+\frac{e}{c}A_y(x)]^2}{2m^*}+\frac{eg^*}{2m_0}\frac{\sigma_z\hbar}{2c}B_z(x)+V\delta(x-x_0), \quad (1)$$

where m^*, m_0, g^* and (p_x,p_y) are the effective mass, the free electron mass, the effective Landé factor and the momentum of the electron, respectively, $\sigma_z=+1/-1$ for spin-up/spin-down electrons, and the magnetic vector potential can be written as $(0,A_y(x),0)$ in the Landau gauge. Because of the translational invariance of the system along the y direction, the solution of the stationary Schrödinger equation $H\Psi(x,y)=E\Psi(x,y)$ can be written as a product $\Psi(x,y)=e^{ik_yy}\psi_{\sigma_z}(x)$, where $\hbar k_y$ is the expectation value of the momentum p_y in the y direction. The wavefunction $\psi_{\sigma_z}(x)$ complies with the following one-dimensional (1D) Schrödinger equation:

$$\{\frac{d^2}{dx^2}+\frac{2m^*}{\hbar^2}[E-U_{eff}(x,k_y,\sigma_z,\chi,V,x_0)]\}\psi_{\sigma_z}(x)=0, \quad (2)$$

where $U_{eff}(x,k_y,\sigma_z,\chi,V,x_0)=\frac{\hbar^2}{2m^*}[k_y+\frac{e}{c\hbar}A_y(x)]^2+\frac{eg^*\sigma_z\hbar}{4m_0c}B_z(x)+V\delta(x-x_0)$ is the effective potential of the electron in the GMR device. The second item in U_{eff} [called the spin-field interaction or the Zeeman coupling between the electron-spin σ_z and the magnetic field $B_z(x)$] is much smaller for GaAs materials than other items in U_{eff}, plays a minor role and thus can be omitted reasonably [11]. Clearly, U_{eff} depends not only on the longitudinal wavevector k_y and the magnetic configuration, but also on the δ-doping, $V\delta(x-x_0)$. In fact, it is the dependence of U_{eff} on the δ-doping that gives rise to the possibility to structurally control the GMR device.

Following the improved transfer matrix method (ITMM) [27], we exactly solve Eq. (2) and the transmission coefficient $T_\chi(E,k_y)$ for the incident electron with energy E and wavevector k_y is readily obtained. Thus, the conductance at zero temperature can be calculated from well-known Landauer–Büttiker theory [28]

$$G_\chi(E_F)=G_0(E_F)\int_{-\pi/2}^{+\pi/2}T_\chi(E_F,\sqrt{2E}\sin\varphi)\cos\varphi d\varphi, \quad (3)$$

where φ is the incident angle with respect to the x direction and $G_0=e^2m^*v_FL_y/h^2$ with the Fermi velocity v_F and the length L_y of the structure in y direction.

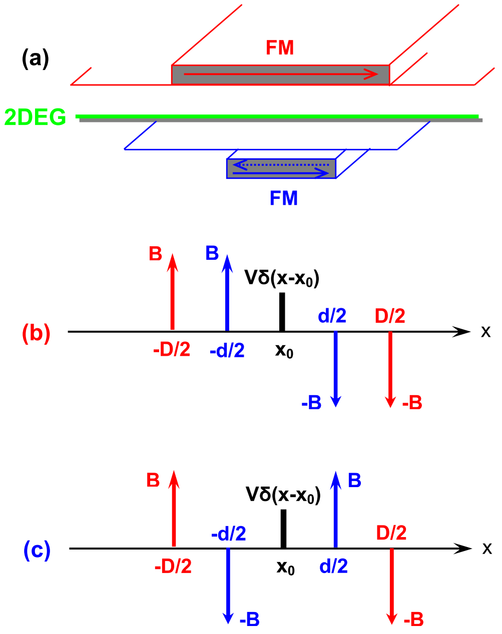

Fig. 1. (a) Schematic illustration of the GMR device: two FM stripes are deposited on top and bottom of the GaAs/Al$_x$Ga$_{1-x}$As heterostructure, (b) and (c) correspond to AP and P alignments of the device, respectively, where a δ-doping $[V_0\delta(x-x_0)]$ is comprised.

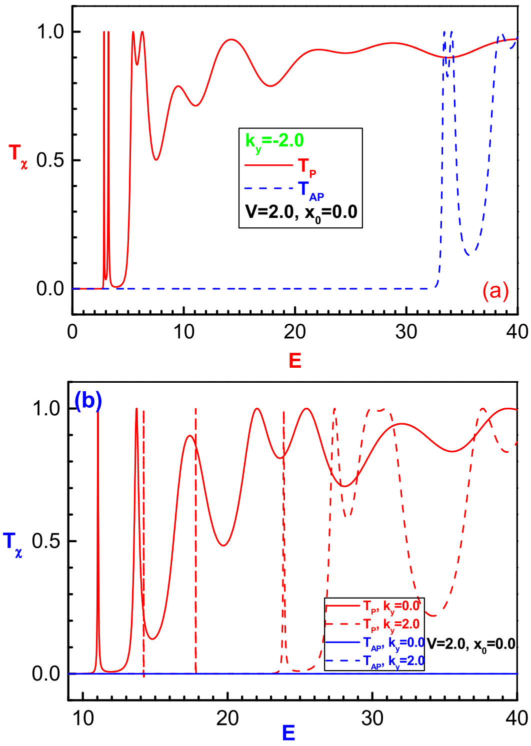

Fig. 2. The transmission probability for the electron tunneling through P and AP magnetizations as the function of the incident energy for (a) $k_y=-2.0$ and (b) $k_y=0.0$ and 2.0, where the δ-doping is assumed to be $V=2.0$ and $x_0=0.0$.

3. Results and discussion

In our numerical calculations, for convenience we express all relevant quantities in the dimensionless form by means of two characteristic parameters: the cyclotron frequency $\omega_c=eB_0/m^*$ and the magnetic length $\ell_B=\sqrt{\hbar/eB_0}$, e.g., $x\longrightarrow\ell_Bx$ and $E\longrightarrow\hbar\omega_cE$. The 2DEG system is taken for GaAs material with $m^*_{GaAs}=$

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