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Theoretical study of the magnetoresistance under electric field in III–V diluted magnetic semiconductor

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Abstract

In this paper we study the magnetoresistance and the coupling energy in heterostructures formed by two magnetic layers $Ga_{1-x}Mn_xAs$ separated by a nonmagnetic spacer GaAs under an electric field and develop a mean-field theory of carrier in diluted magnetic semiconductor. Our main result indicates that magnetoresistance can be dramatically suppressed by an external electric field.

Keywords: GaMnAs; Magnetic semiconductor; Semiconductor; Mean field theory; Magnetoresistance; Coupling energy

1. Introduction

Semiconductor devices based on the control and manipulation of electron spin (semiconductors spintronics) have recently attracted considerable attention since the discovery of ferromagnetism with high Curie temperature T_C near 100 K [1] in a number of conventional semiconductors. Room temperature ferromagnetic semiconductors have great potential to be of use in magnetoelectronics and spintronics. Therefore a large effort is on in two directions: first, the study of the origin of ferromagnetism and of high Curie temperature magnetic semiconductors [2–7]; and, second, the design and growth of devices and heterostructures for magnetoelectronics and spintronics [8–11]. Special attention has been focused on $Ga_{1-x}Mn_xAs$ alloys, which exhibit very interesting magnetic and transport properties. Mn atoms have five electrons in the 3d levels and two electrons in the 4s levels, and their incorporation into the GaAs matrix plays two roles: they act both as $S = \frac{5}{2}$ local moments, and as acceptors generating hole states in the material. A large amount of these holes are trapped on antisite n-type deep defects present in the host semiconductor, since these materials are grown at low temperature [12]. The rest of the holes, with a concentration $p \ll x$, are responsible for the occurrence of ferromagnetic order in DMS. The system is formed by two interacting subsystems: a subsystem of Mn ions, which are so diluted that interaction between their magnetic moment is negligible, and a subsystem of

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carriers. Without interaction between them, both subsystems should be paramagnetic at any temperature. However, antiferromagnetic Hund's coupling, J, between the carrier's and the Mn spins makes the two subsystems become ferromagnetically ordered and antiferromagnetically coupled. In this work, we investigate the electrical, magnetic and transport properties as a function of a band offset V_w and an external electric field. Our main results indicate that by the mean of an electric field we can control the coupling between the two magnetic layers and we strongly modify the magnetoresistive effect in our heterostructure.

2. The model

DMSs layers are described by the following Hamiltonian [13]:

$$H = H_{\mathrm{h}} + J\sum_{I,i} S_I s_i \delta(R_I - r_i) + W\sum_{I,i}\delta(R_I - r_i). \quad (1)$$

The first term describes the carriers. It is the sum of the kinetic energy of the holes and the hole–hole interaction energy. For the range of carrier density of interest in DMSs, the carrier–carrier interaction is not relevant and we neglect it. We treat kinetic energy in the framework of the envelope function approximation. In this approach, we describe the hole electronic states of the host semiconductor by a parabolic band. The second term proportional to J is the antiferromagnetic exchange interaction between the spin of the Mn^{2+} ions located at R_I, and the spins s_i of the itinerant carriers located at r_i. The last term is an interaction between carrier charge n_i and potential arising from magnetic dopants. We solve Hamiltonian (1) in the mean field approximation: in this approach, similar to the Jellium model, local magnetic interaction of spin carriers with Mn spins is substituted by interaction with an effective magnetic field of intensity $V_c = S_I J x/a^3$ [13]. In this expression a^3 is the unit cell volume of the host semiconductor, S_I is the ion spin and J is the antiferromagnetic Hund's coupling. In the same model the electronegativity difference between the carriers and Mn ions is described by an effective potential of interaction $V_w = Wx/a^3$, Since there is no reliable experimental information on the value of W. We consider it as a parameter in the range $0 < W < J$. Within this approach, in our heterostructure holes are free to move in the x–y plane and one-particle wave functions and eigenvalues have the following forms:

$$\Psi^{\mathrm{F(AF)}}_{i,\vec{k},\pm} = \frac{\exp(i\vec{k}\cdot\vec{r})}{\sqrt{s}}\Phi^{\mathrm{F(AF)}}_{i,\pm}(z),$$

$$E^{\mathrm{F(AF)}}_{i,k,\pm} = \frac{\hbar^2\vec{k}^2}{2m_{\parallel}} + \varepsilon^{\mathrm{F(AF)}}_{i,\pm}.$$

Here S is the areal dimension of the sample, $\vec{r}$ and $\vec{k}$ are position and momentum of carriers in the plane perpendicular to the growth direction z, i denotes subband index, and $\Phi^{\mathrm{F(AF)}}_{i,\pm}(z)$ and $\varepsilon^{\mathrm{F(AF)}}_{i,\pm}$ are obtained from the one-dimensional Schrödinger equation in the z-direction:

$$-\frac{\hbar^2}{2m^*}\frac{\partial\Phi^{\mathrm{F(AF)}}_{i,\pm}(z)}{\partial z^2} + V^{\mathrm{F(AF)}}_{\mathrm{tot}}(z)\Phi^{\mathrm{F(AF)}}_{i,\pm}(z) = \varepsilon^{\mathrm{F(AF)}}_{i,\pm}\Phi^{\mathrm{F(AF)}}_{i,\pm}(z), \quad (2)$$

where m^* is the effective mass in the z direction.

$$V^{\mathrm{F(AF)}}_{\mathrm{tot}}(z) = V^{\mathrm{F(AF)}}_{\pm}(z) + eFz,$$

where $V^{\mathrm{F(AF)}}_{\pm}(z)$ is an effective potential and has the following forms [13]:

$$V^{\mathrm{F(AF)}}_{\pm}(z) = \mp V_c + V_w \quad \text{for} \quad 0 < z < d_m,$$

$$V^{\mathrm{F(AF)}}_{\pm}(z) = 0 \quad \text{for} \quad d_m < z < d_m + d_p,$$

$$V^{\mathrm{F(AF)}}_{\pm}(z) = \mp\sigma_{\mathrm{F(AF)}}V_c + V_w \quad \text{for} \quad d_m < z < 2d_m + d_p,$$

$$V^{\mathrm{F(AF)}}_{\pm}(z) = \infty \quad \text{otherwise}, \quad (3)$$

where $\sigma_{\mathrm{F(AF)}}$ is $+1$ in the ferromagnetic (F), (-1) (antiferromagnetic) (AF) coupling case, $(\pm)$ is the carriers spin index, up $(+)$ or down $(-)$. Effective potential can be designed by the profiles shown in Fig. 1 for two different couplings between magnetic layers $Ga_{1-x}Mn_xAs$ and nonmagnetic GaAs spacer, taking into account the different spin orientations.

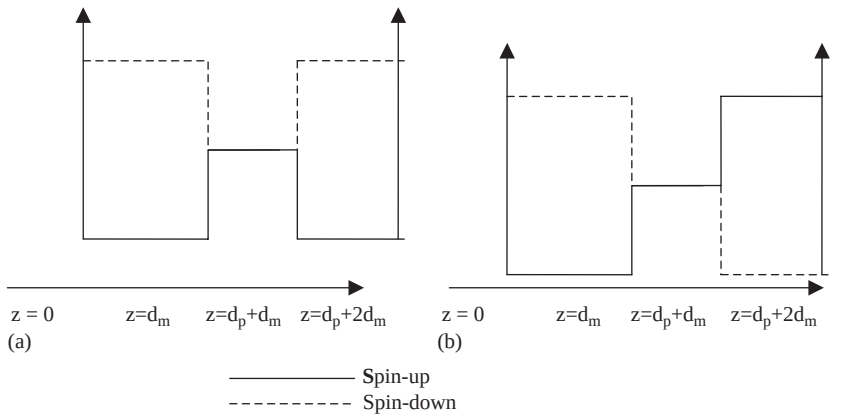

Fig. 1. Potential profiles for both spin carrier directions in F and AF configurations. (a) Ferromagnetic coupling. (b) Antiferromagnetic coupling.

3. Results and discussion

The spin dependent density of holes is given by the following expression:

$$n_{\pm}^{\mathrm{F(AF)}}(z) = \sum_{i,\pm} \int \frac{\mathrm{d}^2k}{(2\pi)^2} \frac{1}{(1+\exp((\varepsilon_{i,\pm}^{\mathrm{F(AF)}}+\varepsilon_k-\mu)/K_{\mathrm{B}}T))} \times |\Phi_{i,\pm}^{\mathrm{F(AF)}}(z)|^2. \quad (4)$$

In expression (4) $\varepsilon_{i,\pm}^{\mathrm{F(AF)}}$ and $\Phi_{i,\pm}^{\mathrm{F(AF)}}(z)$ are obtained from Eq. (2) and $\varepsilon_k = \hbar^2k^2/2m^*$ denotes the plane wave energy from the inplane motion, $m_{\|}$ is effective mass in the inplane motion. We solve Eqs. (2)–(4) using the finite difference technique [14,15]. For convenience we express the density of the holes with $n_0 = (a_{\mathrm{B}})^{-3}$, where $a_{\mathrm{B}} = 4\pi\varepsilon_0\kappa\hbar^2/2m_{\|}$ is the effective Bohr radius of holes, and the energy with the effective Rydberg $R_y = e^2/4\pi\varepsilon_0\kappa a_{\mathrm{B}}$, and the electric field with $F_0 = eR_y/a_{\mathrm{B}}$. μ represents the chemical potential and determined from the neutrality condition $\int(n_+(z)+n_-(z)-C)\,\mathrm{d}z = 0$.

$m^* = 0.5m_0$, $m_{\|} = 0.09m_0$, where m_0 is the free electron mass. $\kappa = 12.7$ is the dielectric constant. $T = 5$ K, $\mu = 53$ meV, $d_m = 30$ Å, $d_p = 30$ Å and $x = 0.05$. We consider that DMS layers have a density of Mn's, $C = 1\ \mathrm{nm}^{-3}$. The exchange integral of $J = 150\ \mathrm{meV\ nm}^3$ is reduced in order to compensate for the absence of spin–orbit interaction in the present calculation.

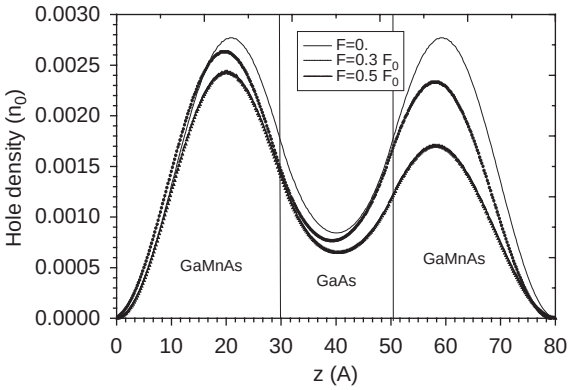

Fig. 2. Spin-down holes density under electric field.

The influence of the electric field on the distribution of holes is shown in Fig. 2 (ferromagnetic coupling). The density increases in the magnetic layer and decreases in the central nonmagnetic GaAs layer. This distribution is symmetric in comparison to the central GaAs layer without an applied electric field, but when the intensity of the applied electric field increases, this symmetry is broken, and strongly modified. The density increases in one of the magnetic layers and decreases in the other. This phenomenon can be thought of as arising from competition between

opposite effects: on the one hand electric field pushes charge distribution to the left, and on the other hand, electronic repulsion prevents charge accumulation on that part of the system. Our results indicate that by the mean of an applied electric field we can modify the charge distribution. Note that the same effect is obtained for the antiferromagnetic coupling.

Semiconductors have lower carrier density than metals, hence exchange coupling energy ($E_{AF}-E_F$) is sensitive to electric field. We evaluated the influence of applied electric field on the type of coupling between the two magnetic layers by summing the energy of the occupied states. We obtained the total energy of the solutions with ferromagnetic E_F, and antiferromagnetic coupling E_{AF} between $Ga_{1-x}Mn_xAs$ layers, the effect of the electric field is introduced by the term eFz in Eq. (2). In Fig. 3, we plot the exchange coupling energy as a function of F for different values of V_w. Application of electrical field changes the density in magnetic layers $Ga_{1-x}Mn_xAs$. As shown in Fig. 2 when the electric field increases the coupling energy decreases and therefore changes its sign. At high electric field intensity one of the DMS layers becomes depopulated and the two magnetic layers become decoupled; therefore coupling energy becomes zero. There is a superimposed fine structure related to the depopulation of subbands originated by the external electric field. Transport parallel to the growth direction presents a large magnetoresistive effect. We evaluated the conductivity in the two ferromagnetic and antiferromagnetic coupling configurations; the expression for conductivity is given by [16] $\mu = (e^2/m^*)\sum_{i,\sigma} \tau_i^\sigma n_i^\sigma / C$. In this expression C is the density of Mn's ions and n_i^σ is the two-dimensional density of carriers in the subband i and spin is σ; the sum is over occupied states and the transport scattering time is given by $1/\tau_i = \beta/\sum_{i,\sigma} A_{i,\sigma,l,\sigma}$. The sum is restricted to occupied states. β is a constant which depends on details of scattering potential and $A_{i,\sigma,l,\sigma} = \int_{DMS} dz\ |\Phi_{i,\sigma}(z)|^2 |\Phi_{l,\sigma}(z)|^2$. This integral is restricted to DMS regions. We have evaluated the conductivity of F and AF solutions and magnetoresistance is given by $MR = (\mu_{AF} - \mu_F)/\mu_{AF}$, which is plotted in Fig. 4 as a function of band offset V_w. In the ferromagnetic case, minority carriers are mainly localized in the central paramagnetic layer, where the scattering is much weaker than in the DMS layers. In the AF coupling case the carriers, for both spin orientations, located on the central layer have a wave function extended in one of the DMS slabs, and therefore they suffer a stronger scattering. The minority spin high mobility channels in the ferromagnetic coupling, localized in the central layer, are responsible for the conductivity difference between the ferromagnetic and antiferromagnetic phases. The peak that appears near $V_w = 0.95V_c$ is a quantum effect due to the occupancy of a new subband in the ferromagnetic phase.

In Fig. 5, we show the magnetoresistance as a function of the external electric field for two values

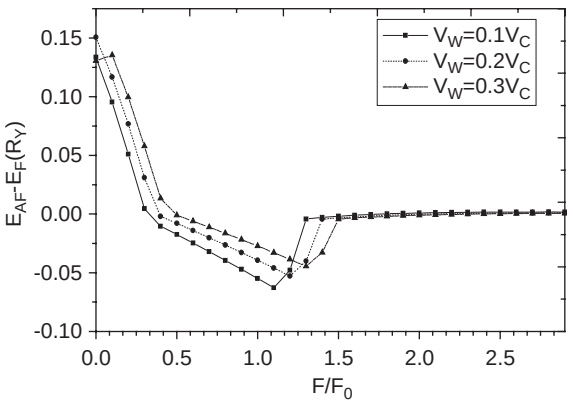

Fig. 3. Coupling energy as a function of external electric field.

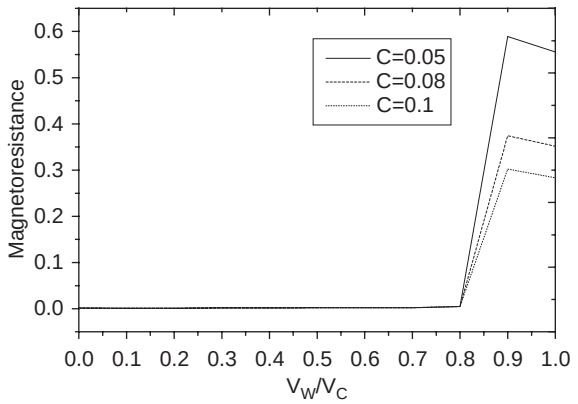

Fig. 4. Magnetoresistance as a function of V_w.

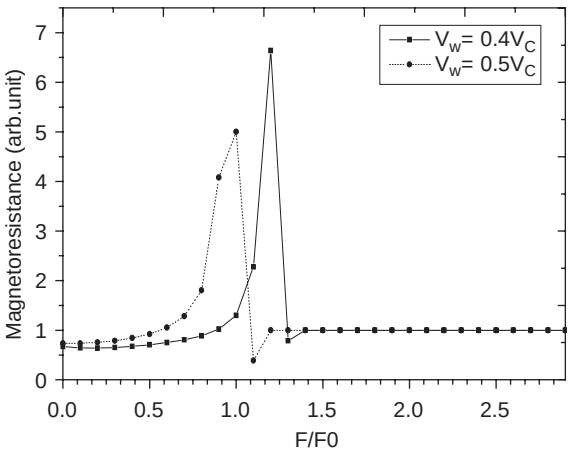

Fig. 5. Magnetoresistance as a function of external electric field.

of V_w. Because the electric field changes the coupling from the ferromagnetic to antiferromagnetic phase, there is a big change in the magnetoresistance when the applied electric field increases. The main point of the results shown in Fig. 5 is the large change in the resistance of the heterostructure when electric field is applied. For the same parameter values of the DMS layers, the magnitude of the electric field necessary to modify the magnetoresistance is around 70 kV/cm, an experimentally accessible value.

4. Conclusion

We have studied a heterostructure formed by two magnetic layers separated by a nonmagnetic GaAs layer under external electric field. Ferromagnetic and antiferromagnetic coupled heterostructures have rather different resistances and present large magnetoresistive effects. Our results show that for fixed parameters of our heterostructure, an external electric field changes the coupling from ferromagnetic to antiferromagnetic coupling, producing a large variation in magnetoresistance that can be modified not by an external magnetic field but by an applied electric field.

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