Journal of Superconductivity: Incorporating Novel Magnetism, Vol. 16, No. 1, February 2003 (© 2003)

Electric Field Induced Suppression of the Magnetoresistance of Dilute Magnetic Semiconductor Trilayers

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Received September 30, 2002

In semiconductor spintronic devices, the semiconductor is usually lightly doped and nondegenerate, and moderate electric fields can dominate the carrier motion. We recently derived a drift-diffusion equation for spin polarization in the semiconductors by consistently taking into account electric-field effects and nondegenerate electron statistics and identified a high-field diffusive regime that has no analog in metals. Here high fields are argued to substantially reduce the magnetoresistance observable in a recent experiment on magnetic-semiconductor–nonmagnetic-semiconductor–magnetic-semiconductor trilayers.

KEY WORDS: magnetoresistance; semiconductor spintronics; spin transport.

1. INTRODUCTION

Semiconductor devices based on the control and manipulation of electron spin (semiconductor spintronics) have recently attracted considerable attention since the discovery of long spin relaxation times and large spin transport distances in semiconductors and various device structures [1,2]. In order to design and fabricate high-performance spintronic devices, a comprehensive understanding of spin transport and injection properties of semiconductors and heterostructures is needed.

In theoretical studies of spin transport and injection in semiconductors [3–6], the spin polarization is usually assumed to obey the same diffusion equation as in metals [7],

$$\nabla^2(\mu_\uparrow - \mu_\downarrow) - (\mu_\uparrow - \mu_\downarrow)/L^2 = 0, \qquad (1)$$

where $\mu_{\uparrow(\downarrow)}$ is the electrochemical potential of up-spin (down-spin) electrons. In this diffusion equation, the electric field does not play any role, and spin polarization decays away on a length scale of L from an injection point. This is reasonable for metals because the electric field $\mathbf{E}$ is screened. For semiconductor spintronic devices, however, the semiconductor often is lightly doped and nondegenerate, and a moderate electric field can dominate the carrier motion. In fact, experiments have shown that electric fields can affect spin diffusion in semiconductors dramatically [8,9].

In Refs. [10–12], we examined the role of electric field on spin transport in semiconductors and in Refs. [11,12] we derived a single drift-diffusion equation for the spin polarization of majority carriers. For nondegenerate semiconductors that equation is

$$\nabla^2(n_\uparrow - n_\downarrow) + \frac{e\mathbf{E}}{k_B T} \cdot \nabla(n_\uparrow - n_\downarrow) - \frac{n_\uparrow - n_\downarrow}{L^2} = 0, \qquad (2)$$

where $n_{\uparrow(\downarrow)}$ is the deviation of up-spin (down-spin) electron density from its equilibrium value $n^0_{\uparrow(\downarrow)}$, k_B the Boltzmann constant, and T the temperature. This equation consistently takes into account electric-field effects and nondegenerate electron statistics. We identified a high-field diffusive regime that has no analog in metals. This regime occurs for field as small as 1 V/cm at low temperatures. Two distinct spin diffusion lengths now characterize spin motion, i.e., up-stream (L_u) and down-stream (L_d) spin diffusion lengths. We applied the spin drift-diffusion equation to several situations, including spin injection from a ferromagnet into a semiconductor, magnetoresistance in magnetic trilayers, and injection through a highly doped interfacial region.

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0896-1107/03/0200-0233/0

Here we describe the application of the spin drift-diffusion equation for nondegenerate systems, Eq. (2), to determine the influence of an electric field on the magnetoresistance of a magnetic semiconductor (MS)/nonmagnetic semiconductor (NS)/MS structure. Here the magnetic semiconductor is a dilute magnetic semiconductor, which lacks any spin-polarization at zero applied field, but becomes highly spin polarized at low temperatures in a moderate laboratory field of ~2 T. A large positive magnetoresistance has been observed in MS/NS/MS structures [13]. We find, however, that this magnetoresistance collapses in the high-field regime. We further show how this collapse can be connected to the different relationship between the spin polarization of current and the spin polarization of density in the high-field regime, suggesting a sensitive test of electric-field effects on spin transport in semiconductors.

2. CURRENT VERSUS DENSITY SPIN POLARIZATION

There are two key definitions of spin polarization in semiconductors. One definition, which we will refer to as the spin density polarization P, uses the density difference between up-spin and down-spin electrons,

$$P(x) \equiv \frac{n_\uparrow - n_\downarrow}{n_\uparrow^0 + n_\downarrow^0} \tag{3}$$

The other, which we will refer to as the current density polarization α, uses the current difference between up-spin and down-spin electrons,

$$\alpha(x) \equiv \frac{j_\uparrow - j_\downarrow}{j_\uparrow + j_\downarrow} \tag{4}$$

The values of these two types of spin polarization are usually different, although they are related. To find the relationship between these two polarizations in a homogeneous nonmagnetic semiconductor, we note that

$$j_\uparrow - j_\downarrow = e(n_\uparrow - n_\downarrow)\nu E + eD\frac{d(n_\uparrow - n_\downarrow)}{dx} \tag{5}$$

where ν is the mobility and D the diffusion constant for the carriers. By using the Einstein relation for nondegenerate systems and the local charge neutrality condition,

$$n_\uparrow + n_\downarrow = 0, \tag{6}$$

we obtain

$$\alpha(x) = P(x) + \frac{k_B T}{eE}\frac{dP}{dx}. \tag{7}$$

We now consider that a continuous spin imbalance is injected at $x = 0$, $(n_\uparrow - n_\downarrow)|_0$, and the electric field is along the $-x$ direction. The spin polarization will gradually decay in size as the distance from the point of injection increases and eventually go to zero at $\pm\infty$. The distribution of the spin polarization then can be described by

$$n_\uparrow - n_\downarrow = (n_\uparrow - n_\downarrow)\,|_0\, \exp(-x/L), \quad x > 0, \tag{8}$$

$$n_\uparrow - n_\downarrow = (n_\uparrow - n_\downarrow)\,|_0\, \exp(x/L_u), \quad x < 0, \tag{9}$$

where we define two quantities L_d and L_u as the downstream [14] and up-stream spin diffusion lengths, respectively,

$$L_d = \left[-\frac{|eE|}{2k_B T} + \sqrt{\left(\frac{eE}{2k_B T}\right)^2 + \frac{1}{L^2}}\right]^{-1}, \tag{10}$$

$$L_u = \left[\frac{|eE|}{2k_B T} + \sqrt{\left(\frac{eE}{2k_B T}\right)^2 + \frac{1}{L^2}}\right]^{-1}, \tag{11}$$

and $L_u L_d = L^2$. For a steady spin imbalance injected at $x = 0$, according to Eqs. (8) and (9),

$$\frac{d(n_\uparrow - n_\downarrow)}{dx} = -\frac{1}{L_d}(n_\uparrow - n_\downarrow), \quad x > 0, \tag{12}$$

$$\frac{d(n_\uparrow - n_\downarrow)}{dx} = \frac{1}{L_u}(n_\uparrow - n_\downarrow), \quad x < 0, \tag{13}$$

and the relation between the spin polarization of current $\alpha(x)$ and the spin polarization of density $P(x)$ can be written as

$$P(x) = \alpha(x)\left(1 - \frac{k_B T}{eEL_d}\right)^{-1} \tag{14}$$

for $x > 0$. Equation (14) is equivalent to Eq (5), in Ref. [14], where the authors studied the magnetization (P) in the presence of a current with a *given* spin polarization (α) in a nondegenerate semiconductor. For $x < 0$.

$$P(x) = \alpha(x)\left(1 + \frac{k_B T}{eEL_u}\right)^{-1}. \tag{15}$$

Thus in semiconductors $P(x)$ is proportional to $\alpha(x)$, and the ratio between them depends on the electric field and its direction.

3. FIELD-DEPENDENT MAGNETO-RESISTANCE IN MS/NS/MS STRUCTURES

In MS/NS/MS structures a strong positive magnetoresistance effect has been observed at low temperatures [13]. The dilute magnetic semiconductors in the structure are unpolarized for $B = 0$, but can have a very high spin polarization at low temperature under a moderate applied magnetic field $B \sim 2$ T. This results in a dramatic difference in resistance at $B = 0$ T and $B = 2$ T at low temperature (magnetoresistance). The electric field driven reduction of this magnetoresistance can be expected based on the different spin injection behaviors in the high-field regime and in the low-field regime.

In the low-field regime $[1 - (k_B T/eEL_d)]^{-1} \sim 0$, and $P(x) \ll 1$. Thus the densities of up-spin and down-spin electrons in a nonmagnetic semiconductor remain the same even in the presence of a fully spin-polarized current. Only *half* of the electrons have the proper spin polarization to contribute to the conductance if the current is 100% spin-polarized, and the resistance of the semiconductor should be twice of that for a unpolarized current. Hence the semiconductor resistance depends strongly on the spin polarization in the low-field regime.

In the high-field regime, however, the symmetry in the trilayer between the two magnetic semiconductor contacts is broken, and the spin polarization of the nonmagnetic semiconductor is determined by the spin polarization of the magnet from which carriers are injected into the semiconductor. This is manifest in Eq. (14) as the high-field limit $[1 - (k_B T/eEL_d)]^{-1} \sim 1$. The spin polarization density P, therefore, is very close to the spin polarization of current α. Even if the current is 100% spin-polarized, the electron density would be also fully spin-polarized, and *all* electrons would contribute to the conductance. In the high-field regime, the semiconductor resistance is therefore only weakly dependent on the injected spin polarization, and the magnetoresistance vanishes.

We now calculate how the magnetoresistance depends on the electric field. The magnetic semiconductor we consider here is degenerate and its spin transport is described by Eq. (1) [15]. We also assume that the interfaces between the two materials are transparent, i.e., zero interface resistance. The magnetizations of the two magnetic semiconductors are identical and parallel, $p_L = p_R = p(\mathbf{H})$, which are zero in the absence of external magnetic field and finite for a given external magnetic field $\mathbf{H}$. The resistance of the nonmagnetic semiconductor, R, would depend on the spin polarization in the magnetic semiconductors because of spin accumulation at the heterostructure interfaces, and is therefore also a function of the external magnetic field.

The resistance of a nonmagnetic semiconductor with conductivity σ_s can be calculated via

$$R \equiv \frac{\mu_0(x_0-) - \mu_0(0+)}{eJ} \tag{16}$$

which certainly would be $R(0) = x_0/\sigma_s$ when attached to unpolarized magnetic semiconductors (zero magnetic field). This resistance in the presence of the spin-polarized magnetic semiconductors when $x_0 \ll L^{(s)}$ (where $L^{(s)}$ is the intrinsic spin diffusion length in the nonmagnetic semiconductor) can be expressed as

$$R(\mathbf{H}) \simeq x_0/\sigma_s + \frac{L^{(m)} p(\mathbf{H})}{[1 - p^2(\mathbf{H})]\sigma_m} \times [2p(\mathbf{H}) - \alpha(0) - \alpha(x_0)]. \tag{17}$$

Here $\alpha(0)$ and $\alpha(x_0)$ are the spin polarization of current at the left and right interfaces, $L^{(m)}$ the spin diffusion length in the magnetic semiconductor, and σ_m the conductivity of the magnetic semiconductor. In the low-field regime we find that the magnetoresistance

$$\frac{\Delta R}{R} \equiv \frac{R(\mathbf{H}) - R(0)}{R(0)} = p^2(\mathbf{H}) \left(1 + \frac{[1 - p^2(\mathbf{H})]\sigma_m x_0}{2\sigma_s L^{(m)}}\right)^{-1}. \tag{18}$$

This magnetoresistance can be significant for an MS/NS/MS structure because of the large $p(\mathbf{H})[p(\mathbf{H}) \sim 1]$ and the small conductivity (relative to ferromagnetic metals) ($\sigma_m \sim \sigma_s$) in the magnetic semiconductors. We would like to point out, however, for ferromagnetic metal/semiconductor/ferromagnetic metal structures, the magnetoresistance is usually too weak to detect because of the conductivity mismatch between metals and semiconductors ($\sigma_m \gg \sigma_s$).

In the high-field regime the magnetoresistance is

$$\frac{\Delta R}{R} = \frac{2p^2(\mathbf{H})}{x_0} \left(\frac{1}{L_u} + \frac{[1 - p^2(\mathbf{H})]\sigma_m}{L^{(m)}\sigma_s}\right)^{-1}. \tag{19}$$

We see from the above expression that the effect of electric field on the magnetoresistance can be described in terms of the field-induced *up-stream* spin diffusion length. Increasing the electric field will decrease the magnetoresistance because L_u decreases with the electric field. Figure 1 illustrates the magnetoresistance as a function of electric field for an

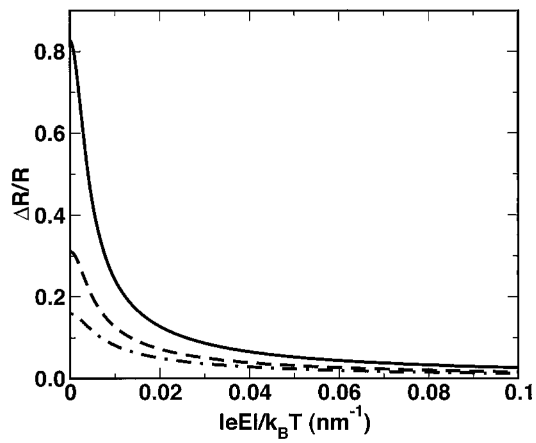

Fig. 1. Magnetoresistance $\Delta R/R$ as a function of electric field. Solid, dashed, and dot–dashed lines correspond to $p(\mathbf{H}) = 0.99$, 0.9, and 0.8, respectively. Other parameters are $x_0 = 1\ \mu$m, $L^{(m)} =$ 60 nm, $L^{(s)} = 2\ \mu$m, and $\sigma_m = \sigma_s$.

MS/NM/MS structure. We see that with an increase of the electric field the magnetoresistance diminishes.

4. CONCLUDING REMARKS

The electric field driven reduction in the magnetoresistance in MS/NS/MS structures is another example of how the physics of spin transport in the high-field diffusive regime for semiconductors differs dramatically from the physics of metallic spin transport. Other phenomena that occur in the high-field regime for semiconductors include the result that for general trilayer FM/NS/FM structures the high field destroys the symmetry between the two magnets present at low fields, where both magnets are equally important to determine spin injection [12]. The efficiency of spin injection into semiconductors in the high-field regime is determined only by the magnet from which carriers are injected into the semiconductor and the magnet that collects the carriers becomes irrelevant. Another consequence is that for FM/NS/NS structures spin injection efficiency in the high-field regime is only determined by the total injected electric current and the distinction between the semiconductors becomes unimportant [12]. This may play a key role in spin injection through a doped Schottky barrier or through an interfacial electron gas (as in Fe/InAs).

ACKNOWLEDGMENTS

This work was supported by DARPA/ARO DAAD 19-01-0490.

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