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Spin-Polarized Current in a Nonmagnetic Conductor and the Role of Electron–Electron Scattering

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The influence of electron–electron scattering on the efficiency of certain methods for the injection and generation of spin–polarized current states in nonmagnetic conductors is discussed. We consider the effect of electron–electron collisions on the resistance to electric transport developing at the interface between a magnetic conductor (MC) and a nonmagnetic conductor (NMC). An essentially unbounded increase of the interfacial MC/NMC magnetoresistance with temperature is predicted.

KEY WORDS: spin injection; hybrid structures.

1. INTRODUCTION AND BASIC EQUATIONS

Several methods for the generation and detection of stationary spin-polarized currents in nonmagnetic semiconductors have been recently proposed and realized [1–6]. Since electron–electron (e-e) scattering may become dominant as the temperature is increased; we analyze here the effect of e-e collisions on the efficiency of some of the proposed methods.

Broadly speaking, currently, two distinctly different methods were proposed for the generation of spin-polarized currents in a nonmagnetic conductor: (i) Injection of a spin-polarized current through the interface between a magnetic conductor (MC) and a nonmagnetic conductor (NMC). In this case, an excess concentration of nonequilibrium electrons with a spin direction as in the MC appears in the NMC boundary layer whose thickness is of the order of the spin relaxation length λ [1]. We will refer to this method as the "spin-filter" scheme. (ii) The "spin-guide" method [6] where, unlike in the spin-filter scheme, the electric current flows along the MC/NMC interface. As a result, a permanent outflow of nonequilibrium electrons with a definite spin polarization is obtained, and an excess of nonequilibrium electrons with the opposite spin polarization appears in the NMC channel; the spin polarization of the current in the NMC channel is opposite to the spin polarization of the current flowing in the surrounding grounded magnetic shell. On first sight it may appear that e-e scattering would be equally detrimental for both of these methods. First, e-e scattering would decrease the spin relaxation length (λ) and, second, the mutual "friction" between electrons of different spins ("spin drag") would tend to equilibrate the momenta of the two spin components. However, these (pessimistic) expectations are not borne true. Considering first the spin-filter scheme we observe that e-e scattering leads to a significant increase of the interfacial magnetoresistance, and thus it facilitates the (desired) generation of spin polarization. In the spin-guide scheme, it turns out that the spin polarization of the current decreases as the e-e collision frequency increases, but it can be shown that the spin polarization of the current density is not susceptible to e-e scattering; the opportunities that the above considerations may open for the development of spin injection methods will be discussed elsewhere.

Here we use the macroscopic transport equations, which were derived by Flensberg *et al.* [7], including e-e scattering. We consider the case of

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infrequent spin-flip scattering, i.e., $\tau_{sf} \gg \tau_{ee}$ (where τ_{sf} is the spin-flip scattering time and τ_{ee} is the e-e scattering time), and thus we ignore the small term (see [7]) associated with nonisotropic spin-flip scattering. Eqs. (1a) and (1b) of Ref. [7] may be written as

$$\mathrm{div}\,\mathbf{j}\uparrow\downarrow = -(\Pi' e/\tau_{sf})(\mu\uparrow\downarrow - \mu\downarrow\uparrow), \quad (1)$$

$$-e^{-1}\nabla\mu\uparrow\downarrow = \rho_i\uparrow\downarrow\,\mathbf{j}\uparrow\downarrow + An\uparrow\downarrow^{-1} \times\ (n\uparrow\downarrow^{-1}\,\mathbf{j}\uparrow\downarrow - n\downarrow\uparrow^{-1}\,\mathbf{j}\downarrow\uparrow),$$

$$\Pi'^{-1} = \Pi\uparrow^{-1} + \Pi\downarrow^{-1}, \quad (2)$$

where $\mu\uparrow\downarrow$ are the electrochemical potentials for the spin-up and spin-down electrons, respectively, $\rho_i\uparrow\downarrow$ are the resistivities due to electron-impurity scattering for the spin-up and spin-down current components, $\Pi\uparrow\downarrow$ are the densities of states at the Fermi surface, $n\uparrow\downarrow$ are the electron densities, and $A \approx \nu_{ee} m\, n_m e^{-2}$ is the e-e spin drag coefficient (see [7]), $\nu_{ee} \propto T^2$ is the e-e collision frequency, and n_m is the lesser of the two spin component electron densities.

2. RESISTANCE OF THE INTERFACE BETWEEN AN IDEAL MAGNETIC MATERIAL AND A NONMAGNETIC CONDUCTOR

A novel large magnetoresistance effect, associated with the injection of a spin-polarized electron current from a dilute magnetic material with a giant Zeeman splitting into a nonmagnetic semiconductor, has been found by Schmidt *et al.* [1]. The effect results from the potential difference that appears near the MC/NMC contact when current flows through the interface; that is, the contact gives rise to a finite resistance for current flow in the circuit. The resistance of the MC/NMC interface originates from suppression of the spin component of the current in the MC as well as in the NMC, occurring over a distance from the interface, which is of the order of the spin relaxation length λ; this behavior is associated with the accumulation (near the interface) of an excess concentration of electrons with this spin component.

It is well known that the e-e interaction does not cause the resistance in a macroscopic conductor because it conserves the total electronic momentum (in the absence of "Umklapp" processes). Electron-electron collisions in conjunction with the scattering processes that do not conserve the electronic momentum (e.g., electron-impurity scattering) lead to an insignificant increase of the resistance. Let us show now

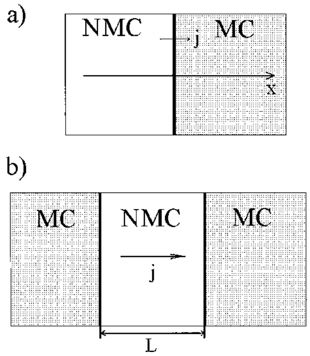

Fig. 1. a) The interface between a magnetic material and nonmagnetic conductor and b) schematic view of the experiment of Schmidt *et al.* [1].

that in the case $\tau_{ee} \ll \tau_i$, the role of e-e collisions dominates the interfacial resistance.

Consider current flow through the interface between two conductors (see Fig. 1a). The transport properties are completely determined by setting $\rho_i\uparrow\downarrow$, $n\uparrow\downarrow$, Π', A, and τ_{sf} in Eqs. (1) and (2) for both regions. We write the electrochemical potentials and currents in the nonmagnetic conductor in the following form:

$$-e^{-1}\mu\uparrow\downarrow = a + bx + c\uparrow\downarrow \exp(x/\lambda),$$

$$j\uparrow\downarrow = d + f\uparrow\downarrow \exp(x/\lambda), \quad (3)$$

where x is measured from the MC/NMC boundary (see Fig. 1a), and the coefficients $a, b, c\uparrow\downarrow, d$, and $f\uparrow\downarrow$ are constants. From Eqs. (1) and (2) we obtain the follwing set of equations for these coefficients and for the spin relaxation length λ:

$$d/b = 1/2\rho_i, \qquad f\uparrow = -f\downarrow,$$

$$-\ (e\lambda)^{-1}c\uparrow\downarrow = 2(\rho_i + 4A/n^2)f\uparrow\downarrow,$$

$$\lambda = (\Pi e^2(\rho_i + 4A/n^2)/\tau_{sf})^{-1/2}, \quad (4)$$

where $\Pi = 2\Pi\uparrow$ is the total density of states, $n = 2n\uparrow$ is the total electron density and $\rho_i = 2^{-1}\rho_i\uparrow$ is the electron-impurity part of the resistivity of the NMC. In the above, the parameters of both spin components in the nonmagnetic conductor are the same.

In an ideal magnetic material only one spin subband is populated (i.e. $n_M\downarrow = 0$). As a result, spin-flip scattering is absent, i.e., $\tau_{sfM} \to \infty$ and $j_M\downarrow = 0$. The electrochemical potential and the current of the nonzero component are obtained from Eqs. (1) and (2) as follows:

$$\mu_M\uparrow = -e\,b_M x, \qquad j_M\uparrow = b_M/\rho_{Mi}\uparrow\,. \quad (5)$$

Matching all potentials and currents at the boundary $x = 0$ yields

$$\Delta R = -e\,a/j = (2)^{1/2}\lambda(\rho_i + 4A/n^2), \qquad (6)$$

where ΔR is the additional resistance of the circuit because of the interfacial potential step, and j is the current density flowing through the boundary, $j = j_{M}\uparrow$.

Thus, in the case $\tau_{ee} \ll \tau_i$, e-e scattering processes influence and determine both the spin relaxation length λ and the added interfacial resistance ΔR. The first is due to the fact that the diffusional mixing of electronic components with different spin orientation is the result of e-e scattering, even though e-e collisions conserve the total momentum. The second (i.e. ΔR) has a very simple physical explanation—that is, in a layer of thickness λ friction will occur between the spin component of the current that passes readily from the NMC to the MC, and that component which is retarded by the interface—this serves as source of resistance. It is most important to note that this effect, in contrast to the effect which is associated with electron-impurity scattering [1], leads to a relative increase of the interfacial contribution to the total resistance of the circuit as the collision frequency increases. Furthermore, when the temperature increases the interfacial resistance will also increase, but the resistance of regions that are far from the interface will not change in a significant manner. Thus, as the temperature is increased the large magnetoresistance effect, characterized by the ratio $\Delta R/R_C$ (R_C is the circuit resistance), should also increase. This behavior would facilitate the generation of the spin polarization in the system.

The difference between the roles of e-e scattering and electron-impurity scattering processes can be clearly demonstrated using an experimental scheme [1] where current flows through a nonmagnetic conductor located between two ferromagnetic contacts, with the length of the nonmagnetic channel L being much shorter than the spin-diffusion length λ, $L \ll \lambda$ (see Fig. 1b). A simple calculation shows the following result:

$$\Delta R = L(\rho_i + 4A/n^2)$$

where the expression on the left is written for the NMC.

Consequently, while in the absence of e-e scattering the resistance of the NMC may change at most by a factor of 2, with the inclusion of e-e scattering effects, the resistance may be increased at will since both spin channels in the NMC may be retarded.

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