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Localization corrections to charge and spin conductivity in ferromagnetic layered structures

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Abstract

Localization corrections to charge and spin conductivity of two-dimensional ferromagnetic systems with spin–orbit interaction are studied theoretically. The corrections lead to negative magnetoresistance — also in the presence of spin–orbit scattering. Magnitude of the corrections depends on the magnetization orientation with respect to the plane of the system. The corrections to spin conductivity are shown to be small.

Keywords: Magnetoresistance; Conductivity; Low-dimensional systems; Spin–orbit interaction

Transport properties of magnetic systems at low temperatures are important in view of possible applications in spintronics [1] and quantum computing [2]. It is known that in nonmagnetic metals and doped semiconductors, quantum corrections are responsible for the anomalous dependence of electrical conductivity on temperature and magnetic field [3,4]. The problem of quantum corrections in ferromagnetic metals is still unexplored. Only a few theoretical works can be found in the relevant literature [5,6], and also a few reports on experiments [7,8]. The experiments proved the existence of quantum corrections related to both localization and electron–electron interaction effects. The theoretical works, on the other hand, considered the effects of localization on the spin-density fluctuations in the vicinity of ferromagnetic transition [5] and also the electron–electron interaction effects in spin quantum wells [6].

The localization corrections in nonmagnetic systems can be suppressed by a sufficiently large magnetic induction **B**. One may expect a similar suppression of weak localization by an internal magnetic induction $\mathbf{B}_{\rm int}$ in ferromagnets. However, numerical estimations show that the internal magnetic induction may only reduce the localization corrections instead of destroying them totally. Apart from this, the demagnetizing factor in thin magnetic films with perpendicular magnetization leads to vanishing internal magnetic induction.

In this paper, we study the localization corrections to conductivity in the presence of spin–orbit (SO) scattering from defects. It is known that in nonmagnetic materials, SO scattering leads to antilocalization, i.e., to positive magnetoresistance at small magnetic fields [9,10]. However, the situation in ferromagnetic metals is different. The processes leading to the antilocalization in nonmagnetic systems are totally suppressed by the exchange field, and one obtains a negative magnetoresistance only.

We consider a Hamiltonian of a two-dimensional (2D) ferromagnet with SO scattering:

$$H = \int d^2\mathbf{r}\, \psi^\dagger(\mathbf{r}) \left[-\frac{\nabla^2}{2m} - M\sigma_z + V(\mathbf{r}) \right] \psi(\mathbf{r}), \tag{1}$$

where the axis z is oriented along the magnetization **M**, $\psi(\mathbf{r})$ is the spinor field, and we put $\hbar = 1$. In the presence of a magnetic induction, the ∇ operator is replaced by $\nabla - ie\mathbf{A}/c$, where **A** is the vector potential. The random potential $V(\mathbf{r})$ consists of the component $V_0(\mathbf{r})$ independent of the electron spin, and the SO component $V_{\rm SO}(\mathbf{r})$.

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Matrix elements of the latter have the form

$$(V_{SO})_{\mathbf{k}\alpha,\mathbf{k}'\beta} = \mathrm{i}\, V_1(\mathbf{k}\times\mathbf{k}')\cdot\sigma_{\alpha\beta} \tag{2}$$

for the transitions $(\mathbf{k},\alpha)\rightarrow(\mathbf{k}',\beta)$, where V_1 is a constant, $\mathbf{k}$ and $\mathbf{k}'$ are the initial and final electron wavevectors, respectively α and β describe the corresponding spin states, and $\sigma=(\sigma_x,\sigma_y,\sigma_z)$ are the Pauli matrices.

The key element of the weak localization theory is a Cooperon [3], which can be presented by a ladder in the particle–particle channel with two propagators describing electrons with small total momentum and close-energy parameters. In the case of ferromagnets and as long as $M\gg\tau^{-1}_{\uparrow,\downarrow}$, where $\tau_\uparrow$ and $\tau_\downarrow$ are the momentum relaxation times of the spin-up and spin-down electrons at the Fermi surface, this channel does not include ladder elements with the Green's functions corresponding to opposite spins. The absence of the singlet Cooperon is the crucial point, which leads to the absence of weak antilocalization.

In a 2D case, the wave vectors are in the plane of the ferromagnet. Consider first the case of in-plane magnetization. For weak scattering and upon averaging over the random field $V(\mathbf{r})$, one finds the bare amplitude of the electron–electron scattering,

$$\Gamma^0_{\alpha\beta\gamma\delta} = \frac{1}{2\pi\nu}\left(\frac{\delta_{\alpha\delta}\,\delta_{\beta\gamma}}{\tau_0} - \frac{\sigma^x_{\alpha\delta}\,\sigma^x_{\beta\gamma}}{\tau^x_{SO}}\right), \tag{3}$$

where τ_0 is the electron relaxation time due to potential scattering, and τ_{SO} is the spin-flip SO scattering time. In a 2D case, the density of states is independent of the spin orientation, $\nu_\uparrow=\nu_\downarrow\equiv\nu$. Calculating the self-energy diagrams, we find the total one-particle relaxation time which is independent of the spin orientation,

$$\frac{1}{\tau_\uparrow} = \frac{1}{\tau_\downarrow} \equiv \frac{1}{\tau} = \frac{1}{\tau_0} + \frac{1}{\tau^x_{SO}}. \tag{4}$$

The Cooperon can be found by calculating the ladder diagrams with the scattering amplitudes given by Eq. (3), which gives

$$\Gamma(\omega,q) = \frac{1}{4\pi\nu\tau^2}\,\frac{1}{-\mathrm{i}\omega+\bar{D}q^2+1/\tau_\varphi}, \tag{5}$$

where $\bar{D}=\frac{1}{2}(D_\uparrow+D_\downarrow)$, the diffusion constants $D_\uparrow$ and $D_\downarrow$ are defined as $D_{\uparrow,\downarrow}=\frac{1}{2}v^2_{F\uparrow,\downarrow}\tau$, v_F is the Fermi velocity, and τ_φ is a phase relaxation time related to inelastic processes [3,4]. The SO scattering enters the Cooperon only through the one-particle relaxation time τ, and has no influence on the pole of the Cooperon. Thus, in the case of in-plane magnetization, we obtain $1/\tilde{\tau}_{SO}=0$, where $\tilde{\tau}_{SO}$ is the effective SO relaxation time of the Cooperon.

Consider now, the case when the magnetization $\mathbf{M}$ is perpendicular to the plane. In this case, we find that the bare scattering amplitudes $\Gamma^0_\uparrow$ and $\Gamma^0_\downarrow$ for up and down electrons (the diagonal elements) are different and have the form

$$\Gamma^0_{\uparrow,\downarrow} = \frac{1}{2\pi\nu\tau_0} - \frac{1}{2\pi\nu\tau^z_{SO\uparrow,\downarrow}}, \tag{6}$$

where $\tau^z_{SO\uparrow,\downarrow}$ are the nonspin-flip SO relaxation times. The total one-particle electron relaxation times are given by

$$\frac{1}{\tau_{\uparrow,\downarrow}} = \frac{1}{\tau_0} + \frac{1}{\tau^z_{SO\uparrow,\downarrow}} \tag{7}$$

and the effective SO relaxation time of Cooperon is

$$\frac{1}{\tilde{\tau}_{SO\uparrow,\downarrow}} = \frac{2}{\tau^z_{SO\uparrow,\downarrow}-2\tau_{\uparrow,\downarrow}} \simeq \frac{2}{\tau^z_{SO\uparrow,\downarrow}} \tag{8}$$

for $\tau^z_{SO\uparrow,\downarrow}\gg\tau_{\uparrow,\downarrow}$. By comparing the results obtained for different magnetic configurations, we see that the effect of SO interaction strongly depends on the magnetization orientation with respect to the plane of the ferromagnet.

The quantum correction to conductivity of a 2D ferromagnet has the form

$$\Delta\sigma = \frac{e^2}{4\pi^2}\left[\ln\left(\frac{\tau_\uparrow}{\tau_{\varphi\uparrow}}+\frac{\tau_\uparrow}{\tilde{\tau}_{SO\uparrow}}\right)+\ln\left(\frac{\tau_\downarrow}{\tau_{\varphi\downarrow}}+\frac{\tau_\downarrow}{\tilde{\tau}_{SO\downarrow}}\right)\right], \tag{9}$$

which is a generalization of the corresponding formula in a nonmagnetic case [3,4]. Here, $\tau_{\uparrow,\downarrow}$ and $\tilde{\tau}_{SO\uparrow,\downarrow}$ are defined, respectively, by Eq. (4) and $1/\tilde{\tau}_{SO\uparrow,\downarrow}=0$ for the in-plane magnetization, and by Eqs. (7) and (8) for the case of perpendicular magnetization. The localization correction, described by Eq. (9), is negative since $\tau\ll\tilde{\tau}_{SO},\tau_\varphi$. The latter inequality means that the momentum relaxation time of electrons is mainly due to the potential scattering.

We can present an expression for the conductivity in the case of a nonzero magnetic induction $\mathbf{B}$ perpendicular to the plane, by generalizing the result for a nonmagnetic 2D system [9]

$$\Delta\sigma(B) = -\frac{e^2}{4\pi^2}\left[\psi\left(\frac{1}{2}+\frac{\tau_{H\uparrow}}{\tau_\uparrow}\right)-\psi\left(\frac{1}{2}+\frac{\tau_{H\uparrow}}{\tilde{\tau}_{SO\uparrow}}+\frac{\tau_{H\uparrow}}{\tau_{\varphi\uparrow}}\right)\right.$$
$$\left.+\psi\left(\frac{1}{2}+\frac{\tau_{H\downarrow}}{\tau_\downarrow}\right)-\psi\left(\frac{1}{2}+\frac{\tau_{H\downarrow}}{\tilde{\tau}_{SO\downarrow}}+\frac{\tau_{H\downarrow}}{\tau_{\varphi\downarrow}}\right)\right], \tag{10}$$

where $1/\tau_{H\uparrow,\downarrow}=4eBD_{\uparrow,\downarrow}/c$, and $\psi(x)$ is the digamma function. The magnetic induction suppresses the negative correction to conductivity, which leads to negative magnetoresistance. It should be noted that the in-plane magnetic induction does not affect the localization correction to conductivity, since the flux of magnetic induction does not penetrate through any closed electron paths [3,4].

One can also find the localization corrections to the spin conductivity, defined as a spin current arising in response to an electric field. In this case, the spin current is the difference of spin-up and spin-down polarized currents, and for the quantum correction, we obtain

$$\Delta\sigma_{\mathrm{spin}} = -\frac{e}{4\pi^2}\ln\left[\frac{D_\uparrow\left(\tilde{\tau}_{\mathrm{SO}\downarrow}^{-1} + \tau_{\varphi\downarrow}^{-1}\right)}{D_\downarrow\left(\tilde{\tau}_{\mathrm{SO}\uparrow}^{-1} + \tau_{\varphi\uparrow}^{-1}\right)}\right]. \qquad (11)$$

The main contributions to the correction, originated from the shortest times $\tau_\uparrow$ and $\tau_\downarrow$, are exactly canceled. Thus, the correction to the spin conductivity is determined only by the SO scattering and the phase relaxation.

In conclusion, we have analyzed the localization corrections to charge and spin conductivity in 2D ferromagnets with SO interactions. The strong magnetic polarization excludes processes with the singlet Cooperon, which are responsible for the antilocalization effect in nonmagnetic materials with SO scattering. As a result, the quantum correction to conductivity is always negative in ferromagnets and leads to negative magnetoresistance. The strength of SO interaction and the phase relaxation time due to inelastic processes determine the magnitude of these corrections. The effective SO scattering time for Cooperon, $\tilde{\tau}_{\mathrm{SO}}$, depends strongly on the magnetization orientation with respect to the system plane. In the case of in-plane magnetization, the inverse time $1/\tilde{\tau}_{\mathrm{SO}}$ vanishes, which significantly enhances magnitude of the localization correction. On the other hand, the localization correction to spin conductivity is very small due to exact cancellation of the contributions from spin-up and spin-down channels in the absence of the SO scattering and phase relaxation.

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