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Conductivity of a disordered ferromagnetic monoatomic film

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Electron transport in the plane of a monoatomic metallic layer with non-zero magnetization is considered. The material is represented by a two-dimensional set of disordered potentials which also possess spins aligned along one axis but not necessarily oriented in one direction. Such a system can be treated as a two-component alloy. The effective cross-section for conduction electrons has been calculated. The total conductivity is obtained within two-current model.

Key words: *electron transport; thin films; disordered material; ferromagnet*

1. Introduction

The study of electron transport properties of very thin magnetic films is very important for constructing nanodevices. Of particular interest is the problem of the resistivity anisotropy in such systems. Camley and Barnaś [1] gave theoretical description of the giant magnetoresistance effects in magnetic multilayers with antiferromagnetic structures using the Boltzmann equation formalism. They explained these effects taking into account roughness of the interfaces and the asymmetry in spin-up and spin-down scattering but they assumed no disorder within the layers. In this work, we consider the conductivity of a monoatomic disordered layer with spontaneous magnetization where the above-mentioned asymmetry of the spin scattering plays a crucial role.

2. Theoretical model

We consider the magnetic monolayer as a system of disordered potentials which additionally have spins aligned along the axis determined by the resultant magnetiza-

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tion. We assume the current to flow along this axis. It actually consists of two currents of electrons polarized up and down. We calculate the behaviour of these types of carriers separately and then compose the total conductivity.

We assume the total potential $U(\mathbf{r})$ to be a sum of two parts

$$U(\mathbf{r}) = U_1(\boldsymbol{\rho}) + U_2(z) \tag{1}$$

where $\boldsymbol{\rho}$ is the position vector in the xy plane, $U_1(\boldsymbol{\rho})$ is a random set of atomic potentials, and $U_2(z)$ represents a geometrical confinement in the z direction [2]. The wave function of electron now can be factorized as follows

$$\psi_s(\mathbf{r}) = \varphi(\boldsymbol{\rho})\,\zeta(z)\,\chi(s) \tag{2}$$

where $\chi(s)$ represents its spin part and s is the spin index ($s = \pm 1$). The interaction of the electron spin $\mathbf{s}$ with the spin $\mathbf{S}$ of an atom at the position $\mathbf{R}_i$ can be described by the operator $u_S(\mathbf{R}_i)$ included in the atomic potential

$$U_1(\boldsymbol{\rho}) = \sum_{i=1}^{N} u_a(\boldsymbol{\rho} - \mathbf{R}_i)\,u_S(\mathbf{R}_i) \tag{3}$$

where $u_a(\boldsymbol{\rho} - \mathbf{R}_i)$ is the usual atomic potential of the ion located at $\mathbf{R}_i$. We define the operator $u_S(\mathbf{R}_i)$ by its matrix elements

$$\begin{cases} \chi(+1)\,u_{+1}(\mathbf{R}_i)\,\chi(+1) = 1, & \chi(-1)\,u_{+1}(\mathbf{R}_i)\,\chi(+1) = 0 \\ \chi(+1)\,u_{+1}(\mathbf{R}_i)\,\chi(-1) = 0, & \chi(-1)\,u_{+1}(\mathbf{R}_i)\,\chi(-1) = t \end{cases} \tag{4}$$

where the parameter $t > 1$. Physically it means that the electron which has its spin directed in accordance with that of an ion scatters only from the Coulomb potential while the electron of opposite spin scatters t times stronger. Spin flip during the scattering is here excluded. Matrix elements of $u_{-1}(\mathbf{R}_i)$ are given by relations analogous with Eq. (4). In general, we can write

$$\chi(s)\,u_S(\mathbf{R}_i)\,\chi(s') = \delta_{ss'}\left(t + (1-t)\,\delta_{Ss'}\right) \tag{5}$$

We now treat the magnetic material consisting of chemically identical atoms which differ with their direction of spin as a disordered binary alloy and apply the scheme of calculation analogous to the Faber–Ziman one [3]. We must take into account that the scattering goes in the plane xy and the Fermi sphere is replaced by a circular sheet of radius $k_{\boldsymbol{\rho}}$ [2, 4, 5]. Let us consider the current of electrons of spin "up". The differential cross-section for scattering of these carriers in plane is [2]

$$\frac{d\sigma_+}{d\phi} = \frac{1}{8\pi k_{\boldsymbol{\rho}}}\left(\frac{m}{2\pi\hbar^2}\right)^2 \left\langle \left| \int \psi^*_{+1}(\boldsymbol{\rho})\,U_1(\boldsymbol{\rho})\,\psi_{+1}(\boldsymbol{\rho})\,d^2\boldsymbol{\rho} \right|^2 \right\rangle \tag{6}$$

We assume the wave functions in the first Born approximation

$$\psi_{+1}(\boldsymbol{\rho}) = \exp\left(i\mathbf{k}_{\boldsymbol{\rho}}\boldsymbol{\rho}\right)\chi(+1) \tag{7}$$

Inserting Eq. (7) into Eq. (6) and making use of Eqs. (4), we obtain

$$\frac{d\sigma_+}{d\varphi} = \frac{1}{8\pi k_{\boldsymbol{\rho}}}\left(\frac{m}{2\pi\hbar^2}\right)^2 u_a^2(q)N\left[c_1 S_{11}(q) + 2(c_1c_2)^{1/2} tS_{12}(q) + c_2 t^2 S_{22}(q)\right] \tag{8}$$

where $u_a(q)$ is the Fourier transform of the atomic potential $u_a(\boldsymbol{\rho} - \mathbf{R}_i)$, $\mathbf{q} = \mathbf{k}'_{\boldsymbol{\rho}} - \mathbf{k}_{\boldsymbol{\rho}}$ is the scattering vector in the *xy* plane, N is the total number of atoms, and S_{ik} are the Ashcroft–Langreth structure factors. The coefficients c_1 and c_2 are the atomic fractions of atoms with spins "up" and "down", respectively, and can be exactly expressed by the relative magnetization μ

$$c_1 = \frac{1+\mu}{2}, \qquad c_2 = \frac{1-\mu}{2} \tag{9}$$

The transport relaxation time can now be calculated using the general formula for in-plane transport given in [2] as

$$\begin{aligned}\frac{1}{\tau_{tr+}} = \frac{1}{4\pi k_{\boldsymbol{\rho}}}\left(\frac{m}{2\pi\hbar^2}\right)^2 nv_F \int_0^{\pi} d\varphi(1-\cos\varphi)u_a^2(q) \\ \times\left[c_1 S_{11}(q) + 2(c_1c_2)^{1/2} tS_{12}(q) + c_2 t^2 S_{22}(q)\right]\end{aligned} \tag{10}$$

where v_F is the Fermi velocity, n is the area concentration of atoms, and q is related with φ by the formula

$$q = 2k_{\boldsymbol{\rho}} \sin\frac{\varphi}{2} \tag{11}$$

The transport relaxation time for inversely polarized electrons is

$$\begin{aligned}\frac{1}{\tau_{tr-}} = \frac{1}{4\pi k_{\boldsymbol{\rho}}}\left(\frac{m}{2\pi\hbar^2}\right)^2 nv_F \int_0^{\pi} d\varphi(1-\cos\varphi)u_a^2(q) \\ \times\left[c_1 t^2 S_{11}(q) + 2(c_1c_2)^{1/2} tS_{12}(q) + c_2 S_{22}(q)\right]\end{aligned} \tag{12}$$

The conductivity in the two-band model reads

$$\sigma = \frac{1}{\rho_+} + \frac{1}{\rho_-} \tag{13}$$

where

$$\rho_\pm = \frac{mL_z}{n_\pm e^2 \tau_{tr\pm}} \tag{14}$$

L_z is the thickness of the layer, and $n_{\pm}$ is the area concentration of carriers of a definite spin.

4. Numerical results

We performed numerical calculations for a model monoatomic disordered layer of iron atoms. The atomic diameter of iron determines the area atomic concentration n and the transversal size of the sample L_z. The scattering potential $u_a(q)$ was calculated as the two-dimensional Fourier transform of the two-dimensional screened Coulomb potential with appropriate screening length. The parameters of the electron gas, k_ρ and v_F, were estimated from the free electron model. Exact calculations of the two-dimensional structure factors S_{ik} are possible in principle [6] but present a time-consuming task. For our model calculations, we approximated S_{11} and S_{22} in the required range of q, i. e. $[0, 2k_\rho]$, by parabolas as in our previous work [4]. Additionally, we assumed them to be identical because they describe the distributions of chemically identical atoms. The structure factor S_{12} takes negative and positive values in the range $[0, 2k_\rho]$ so that the respective part of the integral in Eq. (12) can be neglected.

The numerically calculated values of the conductivity σ in function of the relative magnetization μ for various values of the asymmetry parameter t are presented in Fig. 1. We can see that the conductivity increases with increasing relative magnetization for $t > 1$ ($t = 1$ denotes no asymmetry of scattering). This enhancement of the conductivity is apparently stronger for the larger values of the asymmetry parameter. This fact may be of great importance for constructing spintronics devices.

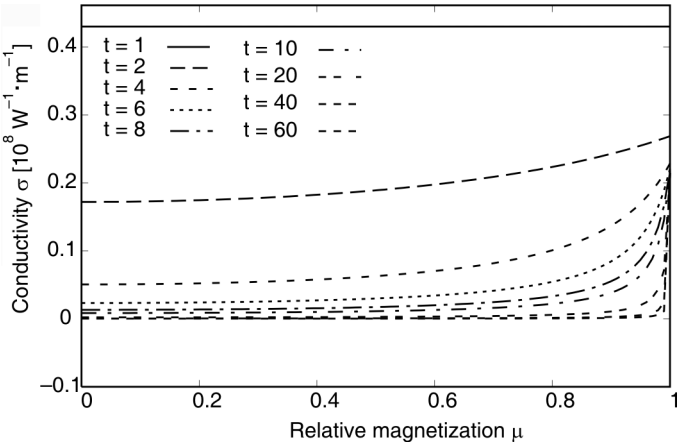

Fig. 1. Dependence of the electrical conductivity σ of a monoatomic Fe film on the relative magnetization μ for a set of values of the asymmetry parameter t

On the other hand, our model allows us to determine the parameter t provided the other parameters of the system are known.

4. Conclusions

The obtained formula allows us to calculate conductivity (or resistivity) of a monolayer film provided all involved physical quantities are known. The only one unknown parameter is t, which measures the asymmetry of the spin scattering. It can be estimated from fitting our formula to the experimentally obtained dependence of the conductivity on magnetization. The knowledge of the parameter t may be important for constructing spintronics devices of desired properties.

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