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Influence of electron–electron scattering on spin-polarized current states in magnetic wrapped nanowires*

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We study the role of electron–electron collisions in the formation of spin-polarized current states in a «spin guide» which is a system consisting of a non-magnetic conducting channel wrapped in the grounded nanoscale magnetic shell. It is shown that under certain conditions the spin guide may generate and transport over long distances the non-equilibrium electron density with a high level of spin polarization, even though the frequent electron–electron scattering leads to a common drift of non-equilibrium electrons. We also propose some ways to convert the spin-polarized electron density into a spin-polarized electric current.

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Spin-guide idea

Spintronic devices based on a spin degree of freedom in addition to charge may lead to new possibilities in the information processing and storage. Efficient spin injection into a semiconductor and long-distance propagation of the spin signal are main requirements for the development of spintronic devices. The basis for the most methods of stationary spin polarization generation is the idea of spin injection through the interface «magnetic conductor (M)–non-magnetic matter (N)», we'll refer it by a «spin-filter» scheme, see, for example, [1–3]. Recently, we have proposed a new method of generation and transportation of high-level spin-polarized currents, namely a «spin-guide» scheme [4]. Spin-guide scheme was proposed as a non-magnetic conducting channel which is wrapped by a magnetic shell whose external boundaries are grounded, see Fig. 1. (Note, there is no need to wrap around the non-magnetic conductor by the magnetic shell, it is enough to contact it with the grounded magnetic material.) Unlike the spin-filter scheme, current flows here along to the M–N interface. The main principle of the spin-guide scheme is based on the removal of the one spin polarization, in contrast with the spin-filter scheme, when spin polarization in a non-magnetic conductor is created by electrons injected from the magnetic material. In the spin-guide scheme those non-equilibrium elec-

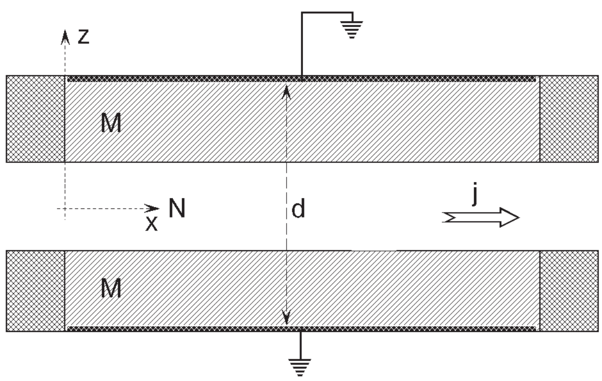

Fig. 1. The spin-guide scheme. Here d is the distance between grounded contacts.

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trons of one of the polarizations (spin-down, for example) which penetrate to M easier then another one, do not return back into the channel due to grounding of outside boundaries of the magnetic shell. So, the polarization of the electric current increases as we get further away from the channel entrance due to spin-down carrier depletion. Note, the spin-guide scheme exploits the withdrawal of the one spin component, so to increase the spin polarization one should decrease the thickens of magnetic region (in contrast to the spin-filter scheme). That is why nanoscale shells are preferable for the spin-guide scheme. As we have shown [4,5] spin guide allows one to alleviate some intrinsic limitations associated with spin-filter schemes: i) the spin polarization of the current in a spin guide can exceed significantly the degree of spin polarization in the magnetic material that is never possible in the spin-filter scheme; ii) the spin polarization of the current may be propagated over arbitrarily long distances, in contrast to the spin-filter scheme where the transport length-scale is of order of the diffusion spin-flip length. In the spin-guide scheme the negative role of spin-flip processes is falls off as to compare with the spin-filter scheme both in the magnetic shell [5] and in the non-magnetic channel too [4]; iii) spin guides allow easy detection and control of the spin polarization and they may form the basis for creating fast spin-polarization switches which do not require magnetization inversion of the magnetic material; iv) one can use one-dimensional wire as non-magnetic channel for the spin guide. As it is known, no-backscattering 1D spin-filter is not possible, if magnetic material is not fully polarized; v) finally, there are a number of spin guide specific effects, some of them allow one direct observation of the spin polarization of the current flowing in a spin guide.

In this paper, we show that, to a large extent, advantageous of spin guides as to compare with spin-filters remain valid even through normal electron–electron (e–e) collisions are the most frequent scattering process.

The role of the electron–electron scattering in spin guides

Normal electron–electron collisions play an essential role in the spin-guide scheme. This is because the e–e interaction leads to a momentum exchange between spin-up and spin-down electron subsystems and, thus, to the establishing of a common drift of the current carriers in the non-magnetic channel. As a result, e–e collisions lead to the depolarization of the current in a spin guide. (There is no the effect in compensated conductors due to the absence of the electric charge transfer at the common drift of carriers.) However, the spin polarization of the non-equilibrium density of carriers is not affected by the e–e scattering (this is in accordance with the conservation of the total spin at these collisions). So, hand in hand with the common drift of the non-equilibrium carriers there is the spin polarization of the density in a spin guide. Accordingly, aforementioned advantageous of the spin-guide scheme are substantially conserved. Below we show that the spin-polarized density may be converted into the spin-polarized current. Therefore, the spin-guide scheme could be rather effective at the temperature increase. Note, under certain conditions normal e–e scattering dominates in a two-dimensional degenerated electron gas in high mobility hetorostructures, see, e.g. [6].

We use macroscopic transport equations, which were derived by Flensberg et al. [7] with taking into account the e–e scattering. We consider the case of the rare spin-flip scattering, i.e. $\tau_{sf} > \tau_{ee}$ (τ_{sf} is the spin-flip scattering time, τ_{ee} is the electron–electron scattering time). We rewrite Eqs. (1,a) and (1,b) of Ref. 7 in the following form:

$$\mathrm{div}\,\mathbf{j}_{\uparrow\downarrow} = -\left(\frac{e\Pi_0}{\tau_{sf}}\right)(\mu_{\uparrow\downarrow} - \mu_{\downarrow\uparrow}), \qquad (1)$$

$$-e^{-1}\nabla\mu_{\uparrow\downarrow} = \rho_{i\uparrow\downarrow}\mathbf{j}_{\uparrow\downarrow} + An_{\uparrow\downarrow}^{-1}(n_{\uparrow\downarrow}^{-1}\mathbf{j}_{\uparrow\downarrow} - n_{\downarrow\uparrow}^{-1}\mathbf{j}_{\downarrow\uparrow}). \qquad (2)$$

Here $\mathbf{j}_{\uparrow\downarrow}$ are the densities of the currents carried by electrons with spin-up and spin-down, respectively, $\mu_{\uparrow\downarrow}$ are electrochemical potentials for the spin-up and spin-down electrons, $\rho_{i\uparrow\downarrow}$ are the resistivities, e is the electron charge, $n_{\uparrow\downarrow}$ are the electron densities, $A \approx e^{-2}m\nu_{ee}n_m$ is the e–e spin drag coefficient [7], $\nu_{ee} = \tau_{ee}^{-1} \propto T^2$ is e–e collision frequency and n_m is the minor of two spin component electron densities; value Π_0 defined by $\Pi_0^{-1} = \Pi_\uparrow^{-1} + \Pi_\downarrow^{-1}$, where $\Pi_{\uparrow\downarrow}$ are densities of states at the Fermi surface. The second term in the right-hand side of Eq. (2) describes the mutual friction of the two spin subsystems, which leads to the common drift of electron system. In the sake of simplicity we ignore the small term, which is related to the anisotropic spin-flip scattering [7].

We consider the simple spin-guide model, i.e. a two-dimensional geometry where the interface is formed by a non-magnetic plate which is surrounded by the magnetic layers with grounded outside boundaries, see Fig. 1. As we concentrate our efforts on the e–e scattering role, we will neglect here by the spin-flip scattering and we consider here fully polarized magnetic layers only (for example, diluted magnetic semiconductors with giant Zeeman splitting or fully polarized half-metals, see [3,8]). Let the x-axis be directed along the channel and lie in it's middle, and take the z-axis to be perpendicular to the interfacial planes, with the origin of the coordinate system located in the center of the entrance into the channel (see Fig. 1). The grounding of the outside boundaries is equivalent to the condition $\mu_{\uparrow\downarrow}(z = \pm d/2) = 0$. For definiteness, let us assume that the magnetic shell is transparent for «spin-down» electrons. For distances from the entrance long enough, so $x >> d$, we have the established solution of Eqs. (1) and (2) given by

$$\mu_{\uparrow} = a + bx, \qquad \mu_{\downarrow} = 0, \tag{3}$$

where a, b are arbitrary constants (the relation between a and b is determined by the boundary conditions at the channel entrance). Writing corresponding currents from the Eq. (2) we see that e–e collisions suppress radically the spin polarization of the current:

$$\alpha \equiv \frac{j_{\uparrow} - j_{\downarrow}}{j_{\uparrow} + j_{\downarrow}} = \left(1 + \frac{A}{\rho_i n^2}\right)^{-1} \approx \left(1 + \frac{\nu_{E-E}}{\nu_i}\right)^{-1}, \tag{4}$$

where ν_i is electron–impurity collision frequency. Thus, as aforementioned above, the spin polarization of the electric current tends to the unity when the electron–impurity scattering dominates over the electron–electron scattering, i.e. $\nu_{ee}/\nu_i \to 0$. And vice versa, α tends to zero (spin currents will tend to be equalized) at increasing spin drag coefficient which is proportional to the e–e collision frequency. On the other hand, the relative spin polarization of the electron density does not depend on the e–e frequency at all:

$$\beta \equiv \frac{\delta n_{\uparrow} - \delta n_{\downarrow}}{eU\Pi} = \frac{\mu_{\uparrow} - \mu_{\downarrow}}{eU}. \tag{5}$$

Here $eU\Pi$ is the maximal possible change of electron density in the potential difference between the ends of the spin guide U, Π is the electron density of states at the Fermi level in the non-magnetic conductor.

Here we should note, that the spin polarization of the electron density may be converted into the practically one-hundred percent spin polarization of the electric current. It may be done in different ways. Firstly, one may use extra local concentration of impurities near the exit from the spin guide, so the electron–impurity scattering dominates over the electron–electron scattering in this region. A comparatively short dirty region, the width of which is of order of the d, will be enough for this purpose. The other way is using of electrostatic constrictions or atomic wires at the exits of the non-magnetic channel; the transport mean free-path in the constriction have to be less then electron–electron mean free path. In the case of atomic wires (one-dimensional quantum point contact) the spin polarization of the current at exit of the spin guide is determined by the ratio between the electrochemical potentials $\mu_{\uparrow\downarrow}$ before the constriction and the electrochemical potential out of channel μ_{∞}. If $\mu_{\downarrow} \le \mu_{\infty}$ then the spin polarization of the current will be 100%.

Note, that if the resistance of the constriction in the end of a spin guide is much higher than the channel resistance, then the spin polarization of the density in the channel β will be constant and it reaches its maximum value: $\beta \approx 1$, i.e. the non-equilibrium density is fully polarized.

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