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

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The role of electron–electron collisions in the formation of spin-polarized current states in a spin guide—a system consisting of a nonmagnetic conducting channel wrapped in a grounded nanoscale magnetic shell—is studied. It is shown that under certain conditions the spin guide can generate and transport nonequilibrium electron density with high spin polarization over long distances even though frequent electron–electron scattering causes drifting of the nonequilibrium electrons as a whole. Ways to convert the spin-polarized electron density into a spin-polarized electric current are proposed.
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1. THE SPIN-GUIDE IDEA

Spintronic devices based on a spin degree of freedom in addition to charge may lead to new possibilities in information processing and storage. Efficient spin injection into a semiconductor and long-distance propagation of a spin signal are the main requirements for the development of spintronic devices. Most methods for producing stationary spin polarization are based on spin injection through a ''magnetic conductor (M)—nonmagnetic matter (N)'' interface; we shall refer to it as a spin-filter scheme (see, for example, Refs. 1–3). Recently, we have proposed a new method for generating and transporting currents with high spin polarization—a spin guide scheme.[4] This scheme was proposed as a nonmagnetic conducting channel which is wrapped in a magnetic shell whose external boundaries are grounded; see Fig. 1. (Note that there is no need to wrap a magnetic shell around the nonmagnetic conductor; a contact between it and the grounded magnetic material is sufficient.) Here, unlike the spin-filter scheme, current flows along the M–N interface. The spin-guide scheme is based on the removal of one spin polarization; this contrasts with the spin-filter scheme where spin polarization is produced in a nonmagnetic conductor by electrons injected from the magnetic material. In the spin-guide scheme nonequilibrium electrons with one type of polarization (spin down, for example) which penetrate to M more easily than electrons with the other type of polarization do not return into the channel because the external boundaries of the magnetic shell are grounded. So, as the distance from the channel entrance increases, the polarization of the electric current increases because of spin-down carrier depletion. Note that the spin-guide scheme exploits the removal of one spin component. Therefore to increase the spin polarization the thickness of the magnetic region must be decreased (in contrast to the spin-filter scheme). That is why nanoscale shells are preferable for the spin-guide scheme. As we have shown elsewhere,[4,5] the spin-guide scheme removes some intrinsic limitations of the spin-filter schemes: 1) the spin polarization of the current in a spin guide can be much greater than the spin polarization in the magnetic material; this is never possible in the spin-filter scheme; ii) the spin polarization of the current can be transported over arbitrarily long distances, in contrast to the spin-filter scheme where the transport length is of the order of the diffusion spin-flip length. In the spin-guide scheme the negative role of spin-flip processes is smaller than in the spin-filter scheme in a magnetic shell[5] and in a nonmagnetic channel;[4] iii) spin guides allow easy detection and control of the spin polarization which do not require magnetization inversion of the magnetic material; iv) one-dimensional wires can be used as a nonmagnetic channel for the spin-guide; it is well known that a no-backscattering 1D spin-filter is impossible if the magnetic material is not completely polarized; v) finally, there are a number of spin-guide-specific effects, some of which enable the spin polarization of the current flowing in a spin guide to be observed directly.

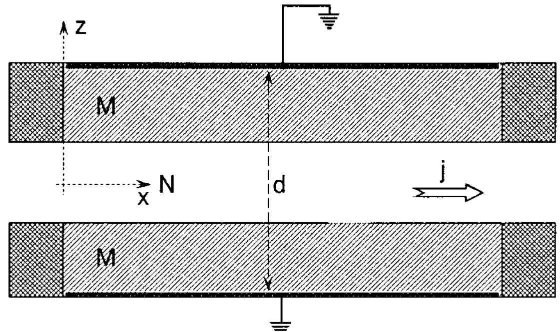

FIG. 1. Spin-guide scheme. *d* is the distance between the grounded conductors.

In this paper we show that the advantages of spin guides over spin filters remain largely valid even though normal electron–electron ($e-e$) collisions are the most frequent scattering processes.

2. THE ROLE OF ELECTRON–ELECTRON SCATTERING IN SPIN GUIDES

Normal electron–electron collisions play an essential role in spin-guide schemes. This is because the $e-e$ interaction leads to momentum exchange between the spin-up and spin-down electron subsystems, thereby establishing a drift of the current carriers as a whole in the nonmagnetic channel. As a result, $e-e$ collisions depolarize the current in a spin guide. (In compensated conductors there is no effect because no electric charge is transferred when the carriers drift as a whole.) However, $e-e$ scattering does not affect the spin polarization of the nonequilibrium carrier density because the total spin is conserved in these collisions. So, together with the drift of the nonequilibrium carriers as a whole there is spin polarization of the density in a spin guide. Accordingly, the aforementioned advantages of the spin-guide scheme are substantially preserved. We shall show below that spin-polarized density can be converted into spin-polarized current. Therefore the spin-guide scheme could become quite effective as temperature increases. Note that under certain conditions normal $e-e$ scattering predominates in a two-dimensional degenerate electron gas in high-mobility heterostructures; see, e.g., Ref. 6.

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

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

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

Here $\mathbf{j}_{\uparrow\downarrow}$ are the current densities of the spin-up and spin-down electrons, respectively; $\mu_{\uparrow\downarrow}$ are the electrochemical potentials of 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 the $e-e$ collisions frequency; n_m is the lower of the electron densities with the two spin components $\Pi_0^{-1}=\Pi_\uparrow^{-1}+\Pi_\downarrow^{-1}$, where $\Pi_{\uparrow\downarrow}$ are the densities of states at the Fermi surface. The second term on the right-hand side of Eq. (2) describes the mutual friction of the two spin subsystems, which leads to drift of the electron system as a whole. To simplify the problem we ignore the small term related to anisotropic spin-flip scattering.[7]

We consider a simple spin-guide model, i.e. a two-dimensional geometry where the interface is a nonmagnetic plate surrounded by magnetic layers with grounded external boundaries; see Fig. 1. Since we are concerned primarily with the role of $e-e$ scattering, we neglect spin-flip scattering and consider completely polarized magnetic layers only (for example, dilute magnetic semiconductors with giant Zeeman splitting or completely polarized semimetals; see Refs. 3 and 8). Let the x axis be directed along and lie in the middle of the channel and the z axis perpendicular to the interfaces, and let the origin of the coordinate system be located at the center of the entrance into the channel (Fig. 1). Grounding the external boundaries is equivalent to the condition $\mu_{\uparrow\downarrow}(z=\pm d/2)=0$. For definiteness, we shall assume that the magnetic shell is transparent to spin-down electrons. For distances from the entrance such that $x\gg d$, the steady-state solutions of Eqs. (1) and (2) are

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

where a and b are arbitrary constants (the relation between a and b is determined by the boundary conditions at the channel entrance). Writing the corresponding currents from Eq. (2) shows that $e-e$ collisions radically suppress 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 the electron–impurity collision frequency. Thus, as mentioned above, the spin polarization of the electric current tends to 1 when electron–impurity scattering predominates over electron–electron scattering, i.e. $\nu_{ee}/\nu_i\to 0$, and vice versa α tends to 0 (the spin currents will tend to be equalized) as the spin drag coefficient, which is proportional to the $e-e$ collision frequency, increases. On the other hand the relative spin polarization of the electron density is completely dependent on the $e-e$ collision frequency:

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

Here $eU\Pi$ is the maximum possible change of the electron density in the potential between the ends of the spin guide U and Π is the electron density of states at the Fermi level in a nonmagnetic conductor.

We note that the spin polarization of the electron density may be converted into essentially 100% spin polarization of the electric current. This can be done in different ways. First, extra local impurity concentration near the exit from the spin guide can be used. Then electron–impurity scattering predominates over electron–electron scattering in this region. A comparatively short dirty region whose width is of the order of d will be adequate for this purpose. Another method is to use electrostatic constrictions or atomic wires at the exits of the nomagnetic channel; the transport mean free path in the constriction must be less than the electron–electron mean free path. For atomic wires (one-dimensional quantum point contacts) the spin polarization of the current at the exit of the spin guide is determined by the ratio between the electrochemical potentials $\mu_{\uparrow\downarrow}$ before the constriction and the electrochemical potential μ_∞ outside the channel. If $\mu_\downarrow\leqslant\mu_\infty$, then the spin polarization of the current will be 100%.

Note that if the resistance of the constriction at the end of a spin guide is much higher than the channel resistance, then the spin polarization β of the density in the channel will be constant, reaching its maximum value $\beta\approx 1$, i.e. the nonequilibrium density is completely polarized.

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