Spin-Guide: A New Source of High Spin-Polarized Current

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We propose a “spin-guide” source for generation of electric currents with a high degree of spin polarization, allowing long-distance transmission of the spin-polarization. In the spin-guide scheme proposed here, a non-magnetic conducting channel is wrapped by a magnetic shell which preferentially transmits electrons with a particular spin polarization. It is shown that this method is significantly more effective than the spin-filter-like scheme where the current flows perpendicular to the interface between a ferromagnetic metal to a non-magnetic conducting material. Under certain conditions a spin-guide may generate an almost perfectly spin-polarized current, even when the magnetic material used is not fully polarized. The spin-guide is predicted to allow the transport of spin polarization over long distances which may exceed significantly the spin-flip length in the channel. In addition, it readily permits detection and control of the spin-polarization of the current. The spin-guide may be employed for spin-flow manipulations in semiconductors used in spintronic devices.

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I. INTRODUCTION

Recently there has been a growing interest in “spintronic” devices, where the spin degree of freedom is utilized for data manipulations, rather than just the electronic charge as in customary devices. This is due to the obvious advantages of integrating a magnetic data storage device with an electronic readout, as well as due to the promising prospects for applications of spin-polarized currents in quantum computing. The main technical requirements for the development of spintronic devices, pertain to: (i) high efficiency spin injection into a semiconductor, and (ii) long-distance propagation of the spin signal. Currently, some of the major issues concerning the fabrication of spintronic devices center on the generation of stationary spin-polarized currents in non-magnetic semiconductors.

Some of the methods for the generation of stationary spin polarization are based on spin injection through the interface between a ferromagnetic metal to a non-magnetic conducting material; we will refer to this idea as the “spin-filter” scheme. In the diffusive transport regime, the spin-filter scheme has been shown initially to be associated with a very small degree of spin polarization (of the order of a few percent). There are two main reasons for this inefficiency. (i) the spin relaxation time is much smaller in a ferromagnetic material than in a non-magnetic one, and (ii) the conductivity of the ferromagnetic metal injector is much higher than the conductivity of the semiconductors which are usually used as non-magnetic materials. In effect, the nonequilibrium electrons that are injected from the ferromagnet, undergo a Brownian motion. Consequently, prior to reaching the detector (collector) these electrons return back into the ferromagnet repeatedly (or they undergo a spin-flip in the semiconductor). Because of the high frequency of spin-flip processes the probability to lose the spin is high in the magnetic material. Furthermore, due to the aforementioned conductivity mismatch between the ferromagnetic and nonmagnetic materials, the electrons will spend most of the time in the ferromagnetic material, and this will increase the probability to lose the excess spin orientation. Consequently, the spin polarization of the current in the semiconductor is expected to be extremely low.

There are number of additional essential limitations inherent to the spin-filter scheme. First, the spin polarization of the injected current can not exceed the spin polarization of the current in the magnetic material (serving as an injector). Secondly, the distance over which a significant degree of spin polarization may be maintained in a non-magnetic material, can not exceed the diffusion spin-flip length in it. In addition, we note that it is practically impossible to vary the spin polarization of the injected current, and additional methods are required in order to detect and/or measure the degree of spin polarization (such as the use of a light emitting diode or the oblique Hanle effect technique).

Recently, the spin-injection efficiency has been markedly increased, indeed, by replacing the ferromagnetic metal by a diluted magnetic semiconductor (DMS), $\text{Be}_x\text{Mn}_y\text{Zn}_{1-x-y}\text{Se}$, a record degree of polarization (up to 90%) has been achieved. This remarkable result originates from specific properties of the DMS. In particular, because of the very large split of the spin subbands in a magnetic field, these compounds may have a sufficiently high degree of spin polarization. Consequently, if the Fermi level in the DMS appears below the bottom of one of the spin subbands, the spin-polarization may reach 100%. However, the use of a DMS instead of a ferromagnetic metal, as well as a number of other ways suggested recently, overcomes only one of the
For the sake of specificity, let us consider a flat configuration where the interface is a planar plate; the extension to the three-dimensional case (cylindrical wire) is straightforward. We will consider the diffusive transport regime, where the diffusion length $l_{\uparrow \downarrow}$ (where $l_{\uparrow \downarrow}$ are the electron-impurity mean-free paths for the spin-up and spin-down electrons, correspondingly) are significantly shorter than any characteristic length of the spin-guide. In this paper the effects of electron-electron collisions are neglected - this is a fortiori valid at sufficiently low temperatures (i.e., several degrees Kelvin).

Let $\mu_{\uparrow \downarrow}$ denote the electrochemical potentials for the spin-up and spin-down electrons, respectively. The electric current densities $J_{\uparrow \downarrow}$ are related to the electrochemical potentials via Ohm’s law

$$J_{\uparrow \downarrow} = -\frac{\sigma_{\uparrow \downarrow}}{e} \nabla \mu_{\uparrow \downarrow}, \quad (1)$$

where $\sigma_{\uparrow \downarrow}$ are the corresponding conductivities. The spin transport, within the diffusive regime approximation, is described by Mott’s equations:

$$\text{div} (\sigma_{\uparrow \downarrow} \nabla \mu_{\uparrow \downarrow}) = \frac{\Pi_0 e^2}{\tau_{sf}} (\mu_{\uparrow \downarrow} - \mu_{\downarrow \uparrow}), \quad (2)$$

Here $\Pi_{\uparrow \downarrow}$ are the densities of states at the Fermi level of the up and down spins, and $\tau_{sf}$ is the spin-flip scattering time. Eqs.(2) hold under the assumption that the spin-flip mean free-paths $l_{\uparrow \downarrow} = \nu_F l_{\uparrow \downarrow} \tau_{sf}$ (where $\nu_F l_{\uparrow \downarrow}$ are the Fermi velocities of the spin-up and spin-down electrons) exceed significantly the diffusion lengths $l_{\uparrow \downarrow}$, i.e., $l_{\uparrow \downarrow}^2 > l_{\uparrow \downarrow}^2$; otherwise, the problem should be studied within the kinetic equation approach. A typical lengthscale on which the equilibrium between the spin subsystems is established is the diffusive length $\lambda = (\sigma_0 \tau_{sf} / e^2 \Pi_0)^{1/2} / \sigma_0$, where $\Pi_0^{-1} = \sigma_{\uparrow \downarrow}^{-1} + \sigma_{\downarrow \uparrow}^{-1}$.

Note that we can find the currents in the spin-guide without separation of the electrochemical potential into the chemical ($\eta$) and electrical ($\varphi$) potential contributions, i.e., $\mu_{\uparrow \downarrow} = \eta_{\uparrow \downarrow} + e \varphi$. These potentials can be easily obtained from the solution for $\mu_{\uparrow \downarrow}$ when the screening radius is much shorter than the size of the spin-guide (which is the case in reality). Then, from the condition of electric neutrality, $\Pi_{\uparrow} \eta_{\uparrow} + \Pi_{\downarrow} \eta_{\downarrow} = 0$, we have

$$\eta_{\uparrow \downarrow} = \Pi_{\downarrow \uparrow} (\mu_{\uparrow \downarrow} - \mu_{\downarrow \uparrow}) / \Pi,$$

$$e \varphi = (\Pi_{\uparrow} \mu_{\uparrow} + \Pi_{\downarrow} \mu_{\downarrow}) / \Pi,$$

$$\Pi = \Pi_{\uparrow} + \Pi_{\downarrow}.$$

The above equations should be supplemented by the imposed boundary conditions. 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 \( \mu_{\uparrow, \downarrow} = 0 \). Taking into account the condition of electric neutrality, we obtain \( \eta_{\uparrow, \downarrow} = \varphi = 0 \). It would appear reasonable to take the same potentials at the channel exit. (An excess of exit potential over the grounded boundaries is equivalent to an inefficient removal of energy into the ground.)

Let an unpolarized current I be driven through the channel entrance. We find that the spin-up and spin-down current densities may be expressed as \( J_{\uparrow, \downarrow} = -e^{-1} \sigma_N \partial \mu_{\uparrow, \downarrow} / \partial x = I / 2 w \). As we show below, at the level of accuracy to which we restrict ourselves in this paper, the result is insensitive to the type of boundary conditions that are imposed at the end faces of the magnetic shell (grounding, or absence of current). We also assume that the conductivity in the non-magnetic channel \( \sigma_N \) is spin independent, and that the conductivity in each region is constant.

For the spin-guide model described above, the diffusion equation can be solved exactly. Instead of quoting here the general solution (which is rather complicated) it is sufficient for our purpose to focus attention on the solutions that hold far way from the ends of the spin-guide. We also assume that the length of the non-magnetic channel, L, is much larger then the width of the spin-guide, i.e. \( L \gg d \), and solve Eqs. (2) through a separation of variables, by introducing the new functions \( \mu_+ = (\sigma_+ \mu_+ + \sigma_- \mu_-) / (\sigma_+ + \sigma_-) \) and \( \mu_- = \mu_+ - \mu_- \).

Due to the symmetry of the system and the boundary conditions at \( z = \pm d / 2 \), we obtain the following solution

\[
\mu_\pm = e^{-kz} f_\pm(z),
\]

where the functions \( f_\pm \) are given by:

\[
f_- = \begin{cases} C \cos(\kappa_M z), & |z| < w / 2, \\
D \sin(\kappa_M (d / 2 - z)), & |z| > w / 2,
\end{cases}
\]

\[
f_+ = \begin{cases} A \cos(kz), & |z| < w / 2, \\
B \sin(k(d / 2 - z)), & |z| > w / 2,
\end{cases}
\]

and

\[
\kappa_{M,N} = \sqrt{k^2 - \lambda_{M,N}^{-2}},
\]

where \( \lambda_{M,N} \) is the diffusion length in the magnetic (M) and non-magnetic (N) regions, respectively. Matching the functions \( \mu_{\uparrow, \downarrow} \), and the current (i.e. the derivatives \( \sigma_{\uparrow, \downarrow} \partial \mu_{\uparrow, \downarrow} / \partial z \)) at \( z = \pm w / 2 \), we can determine the values of the coefficients \( A,B,C \) and \( D \) (in terms of the value of one of them), as well as find the possible values of the damping factor k. To exponential accuracy, it is sufficient to consider only the solution with the smallest value of k. The physical meaning of \( k^{-1} \) is quite obvious: it is the distance in the x-direction which an electron will traverse diffusively before it will reach the grounded contact.

In general the solutions given by Eqs. (3) are not applicable at distances from the channel ends which are less than \( k^{-1} \). But, under the assumption that \( L \gg k^{-1} \), and to the accuracy of our analysis, we may use these solutions even near the channel exit. As shown below this amounts to a neglect of a preexponential factor in the expression for the current spin polarization.

Before closing this section, let us consider another type of solution which is valid for distances from the entrance where spin-flip processes have not yet occurred. In the absence of spin-flip Eqs. (2) for \( \mu_+ \) and \( \mu_- \) become independent and a separation of variables can be accomplished separately for each potential. Thus, we have

\[
\mu_{\uparrow, \downarrow} = e^{-k_{\uparrow, \downarrow} z} f_{\uparrow, \downarrow},
\]

with

\[
f_{\uparrow, \downarrow} = A_{\uparrow, \downarrow} \cos(k_{\uparrow, \downarrow} z) \quad \text{at} \quad |z| < w / 2,
\]

\[
f_{\uparrow, \downarrow} = B_{\uparrow, \downarrow} \sin(k_{\uparrow, \downarrow} (d / 2 - z)) \quad \text{at} \quad |z| > w / 2.
\]

From the matching conditions at \( z = \pm w / 2 \) the following transcendental equations are obtained for the damping factors

\[
\tan(k_{\uparrow, \downarrow} w / 2) \tan(k_{\uparrow, \downarrow} (d - w / 2)) = \sigma_{M,N} / \sigma_N. \quad (6)
\]

In the next section we use the above solutions Eqs. (3) - (6) in the analysis of several limiting situations for different spin-guide parameters.

### III. RESULTS

#### A. A fully polarized magnetic region

A most effective implementation of the spin-guide involves the use of a DMS with a very large Zeeman splitting as the magnetic environment, so that the electrons in the magnetic material are fully spin-polarized. Clearly, spin-flip process in the magnetic region are precluded in this case. For definiteness, let us assume that the magnetic shell is not transparent for "spin-up" electrons, i.e. \( \sigma_{M+} = 0 \).

We consider the case when the spin polarization of the current in the channel is high enough, i.e. the width of the non-magnetic channel \( w \) is less than the spin-flip length \( \lambda_N \). This situation is quite real: in particular, we note that since the spin-flip process is of relativistic origins it is characterized by a large spin-flip length in non-magnetic semiconductors, i.e. up to 100 \( \mu m \).
For distances from the entrance short enough so that no spin-flip processes have occurred, the current \( I_t \) will be conserved inside the channel (that is, it does not depend on \( x \)). On the other hand, the current of electrons with the opposite spin direction, \( I_+ \) will decrease exponentially with distance from the entrance into the channel, i.e. \( I_t \propto \exp(-k_t x) \).

According to Eq. (6) we have \( k_t = 0 \), and \( k_\uparrow \) will depend on the ratio \( \sigma_{M\uparrow}/\sigma_N \). Accordingly, for \( \sigma_{M\uparrow} = \sigma_{N} \) the damping factor \( k_\uparrow = \pi/\lambda_d \). If the conductivity of the magnetic shell is much higher than that of the non-magnetic channel, i.e. when \( \sigma_{M\uparrow} > > \sigma_{N} \), the damping factor takes the value \( k_\downarrow = \min\{\pi/w, \pi/(d-w)\} \). Consequently, the spin polarization of the current at the channel exit tends exponentially to unity with increasing \( L \), that is \[
\alpha = \frac{I_t - I_\downarrow}{I_t + I_\downarrow} \approx 1 - e^{-k_\downarrow L}. \tag{7}
\]

Note that the difference between \( \alpha \) and unity, which decreases for larger distances, is determined here only within a pre-exponential factor.

We turn now to analysis of the role of spin-flip processes in the non-magnetic channel. Using Eqs. (3) and (7) we obtain

\[
k_\downarrow^{-1} = \lambda_N \tag{8}
\]

and

\[
1 - \alpha = \frac{w(3d - 2w)}{12\lambda_N^2} \leq \frac{wd}{\lambda_N^2} \ll 1. \tag{9}
\]

Thus, the exponential decrease of \( 1 - \alpha \) (recall Eq. (4)) is bounded below by the value given in Eq. (8). Consequently, the spin polarization remains constant and sufficiently high for all distances away from the entrance. However, both the spin-up and spin-down currents \( J_{t,\uparrow} \) or \( J_{t,\downarrow} \) will decay exponentially with the same damping factor \( k \). The total current will decay as the spin-up electrons succeed in leaving the non-magnetic channel due to spin-flip processes.

### B. A non-ideal magnetic region

In this section, we discuss the situation when the magnetic shell which surrounds the conducting non-magnetic channel is not fully polarized - in this case both spin-up and spin-down currents flow through the shell and spin-flip processes are possible. The coefficient of selective transparency of the magnetic shell is determined by the relation

\[
\gamma = \frac{\sigma_{M\uparrow}}{\sigma_{M\downarrow}} < 1. \tag{10}
\]

This parameter determines the upper bound value of the spin polarization \( \alpha = (1 - \gamma)/(1 + \gamma) \) in the spin-filter scheme. For simplicity, we will neglect in the following spin-flip processes in the non-magnetic channel.

We consider first the case where we may neglect the spin-flip processes in the magnetic shell near the entrance to the spin-guide. Then, according to Eq. (4), the spin polarization of the current in the channel will tend exponentially to the unity,

\[
\alpha \approx 1 - e^{-(k_t - k_\uparrow)x}. \tag{11}
\]

Moreover, from Eqs. (10) and (6) we have \( k_\downarrow > k_\uparrow \).

As shown in the previous section, \( k_\downarrow^{-1} \leq d \), and for \( \sigma_{M\uparrow} \ll \sigma_{N} \) the spin-up current decays on a length-scale which is large compare to \( d \), i.e.

\[
k_\uparrow = 2\sqrt{\frac{\sigma_{M\uparrow}}{\sigma_N w(d-w)}}. \tag{12}
\]

Now we consider the role of spin-flip processes in the magnetic shell. As discussed above, the exponential decrease of the currents \( J_{t,\uparrow} \) (as a function of distance away from the channel entrance) occurring with the corresponding damping factors \( k_{\uparrow,\downarrow} \) will be changed due to the spin-flip processes in such a way that both the up and down components of the current will decrease with the same damping factor \( k \). Assuming that the diffusion of the electrons to the grounded boundaries occurs with a faster rate than the spin-flip processes, i.e. that the condition \( \lambda_M \gg (d-w) \) is fulfilled, we obtain (to a first approximation) that the damping factor \( k \) is the same as \( k_\uparrow \) determined from the Eq. (10). The reason is that the overall damping rate is governed by that component which takes more time to reach the grounded boundaries. The spin polarization \( \alpha \) which arises at such length-scale (measured from the channel entrance) can be found by matching the solutions of Eq. (11) and expanding them in terms of the small parameter. Thus, we obtain:

\[
1 - \alpha = \frac{\gamma}{2(1 - \gamma^2)(k\lambda_M)^2} \cdot \left( \frac{k(d-w)}{\sin k(d-w)} - 1 \right). \tag{13}
\]

In conjunction with Eq. (11) for \( k = k_\uparrow \), Eq. (13) determines a high enough degree of the spin polarization:

\[
1 - \alpha \approx \gamma(d-w)^2/\lambda_M^2(1 - \gamma^2) \ll 1.
\]

We remark that this inequality will be violated if \( \gamma \) is too close to the unity, i.e. in this case our expansion is inapplicable.

In conclusion, we obtained that in the spin-guide scheme 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 the order of the diffusion spin-flip length \( \lambda \). There are additional essential differences between the two schemes. Unlike the spin-filter scheme, the spin polarization \( \alpha \) in the spin-guide does not depend on the ratio \( \sigma_{M\uparrow}/\sigma_N \). Moreover, as may be seen from Eqs. (11) and (13) the
degree of spin polarization in the non-magnetic channel can exceed significantly the degree of spin polarization in the magnetic material.

In the case that $\lambda_M \gg d$, a sufficiently high degree of spin polarization may be achieved when the condition $\gamma(d - w) << \lambda_M$ is fulfilled, i.e.

$$1 - \alpha = \frac{\tan k (d - w)}{2k\lambda_M} \approx \frac{d - w}{\lambda_M} << 1. \quad (14)$$

If the magnetic shell is too thick, i.e. when $\gamma(d - w)/\lambda_M \gg 1$, then the spin polarization of the current will be low.

As aforementioned, to increase the spin polarization one should decrease the width of magnetic region. To this end, the ballistic regime when $(d - w) \ll l_M$, $l_M^2/\gamma \ll 1$ is most favorable. A calculation which goes beyond the framework of the diffusion approach yields in the ballistic limit the following result:

$$1 - \alpha \approx \gamma \frac{l_M(d - w)}{\lambda_M^2} \ln \left( \frac{l_M}{(d - w)(l_M^2/\gamma + 1)} \right). \quad (15)$$

The logarithmic factor in this formula reflects an enhancement of the spin-flip probability for electrons grazing along a magnetic layer.

IV. SPECIFIC EFFECTS AND POSSIBLE EXPERIMENTAL REALIZATIONS

In this section we consider some possible experimental schemes aiming at realization of the proposed transport phenomena, and at direct observation of the spin polarization of the current flowing in a spin-guide.

A. Spin drag

We begin with a discussion of an alternative scheme to the one discussed above, for obtaining the spin-guide effect on the polarization of the electric current. This alternative scheme is based on a new spin-drag effect that can be realized in a geometry of two semiconductor channels separated by a magnetic interlayer (see Fig. 2).

Let a non-polarized current enter into the nonmagnetic (semiconductor) channel 1. In the case of a fully polarized magnetic interlayer a fully polarized current will appear in the semiconductor channel 2 due to the spin-filter effect, i.e. $|\alpha_2| = 1$. At the same time, a polarization $\alpha_1$ will appear in the first channel due to the spin-guide effect, and its magnitude will depend on the relative width of the channels. If the thickness of the magnetic interlayer is taken to be less than the values of $w_1$, $w_2$ and $L \gg w_1, w_2$ (where $L$ is the channel length), we have

$$\alpha_1 = \frac{w_2}{w_2 + 2w_1}. \quad (16)$$

The polarizations of the currents in channels 1 and 2 are opposite to each other, and the total current in the two channels is non-polarized. It is of interest to note that if channel 2 is sufficiently wide such that $w_1 \ll w_2$, the polarized currents will be equally divided between the channels, i.e. an entirely polarized current $J_2 = J_0/2$ will appear in channel 1, with an equal value and opposite polarization to that in channel 2. In the derivation of Eq. (16) we have assumed that the potential applied at the exit of channel 2 is the same as that applied at the exit of channel 1 (the latter is determined in our model by the value of the current $J_0$). Varying the potential at the exit of channel 2, one can control the current polarization in the channels.

In case that the magnetic interlayer is not fully polarized, but $\gamma \ll 1$, the spin polarization determined by Eq. (16) is conserved at distances $L < R$, where $R = \min\{(Rw_N/\sigma_M)^{1/2}, \lambda_N\}$ and $r = \min\{d_M, \lambda_M, l_M^2\}$. Here we take into account the possibility that the propagation of the electrons in the magnetic interlayer is either diffusive or ballistic. If the magnetic interlayer is wider than the non-magnetic channels, i.e. $d_M > w_1, w_2$, then the Sharvin resistances of the exit constrinctions of the system should be used in the expressions for $\alpha_{1,2}$.

The above considerations lead us to suggest the creation of a fast switch of the spin polarized current, achieved by combining the spin drag scheme with electrostatic gates at the exits of the channels one may switch the spin polarization of the current at a fast rate without switching the magnetization of the magnetic material. In the spin-filter scheme fast switching of the current spin polarization is unachievable even under the best conditions, i.e. when using DMS structures. This is because of the required applied high magnetic fields, and the comparatively long relaxation times of the atomic magnetic moments. On the other hand, as mentioned above the
direction of the spin polarization in the spin-guide is opposite to that appearing in the spin-filter scheme at the same polarization of the magnetic material. Therefore, it may be possible to create an alternative switching scheme that combines the spin-filter and the spin-guide schemes with controllable electrostatic gates.

B. Giant magnetoresistance and direct measurement of the current spin polarization

In this section we discuss certain physical effects which could be utilized for the detection and measurement of the current spin polarization.

A spin-guide consisting of a DMS magnetic shell should exhibit a giant magnetoresistance effect. The effect is associated with the decrease of the conductance in the channel (to an essentially vanishing value) upon switching-off of the magnetizing field; the reverse happens when the magnetizing field is switched-on, i.e., a current appears in the channel. This is caused by the fact that the disappearance of all the nonequilibrium electrons at the grounded boundaries is faster than the rate of their arrival to the channel exit. This effect may result in a most significant change of the resistance of the device with a magnetizing field, perhaps even larger than the giant magnetoresistance effect measured in the spin-filter scheme.

If the ferromagnetic material which surrounds the non-magnetic channel in a spin-guide is not fully polarized, a giant magnetoresistance effect may be observed for the case of mutually opposite magnetizations of the upper and lower magnetic layers (see Fig. 1) to avoid the residual magnetization. If the upper and lower magnetic layers have the same magnetization then there is a current at the channel exit, but if their magnetizations are opposite then the current will essentially vanish. Therefore, by changing the applied magnetic field we may change the resistance of the device.

Another spin-guide effect may be observed by locking a non-magnetic channel far from the entry and exit by an electrostatic gate, as shown schematically in Fig. 3. In this case, the essential variation of the current indicates the effectiveness of the spin guide.

At last, in spin-guide with blocked channel and fully polarized magnetic shell one can measure the spin-polarization $\alpha$ directly:

$$ \alpha = 1 - \frac{I(B \neq 0)}{I(B = 0)} $$

here $I(B \neq 0)$, $I(B = 0)$ are currents at exit of spin-guide at switched-on and switched-off magnetized magnetic field correspondingly, both in case of locked gate.

The spin polarization of the current in a spin-guide with a DMS shell can be measured directly by locking a non-magnetic channel far from the entry and exit by an electrostatic gate, as shown schematically in Fig. 3.

V. DISCUSSION

The main operational principle of a spin-guide is the removal of one of the components of the spin current from the channel due to the selective transparency (with respect to the spin direction) of a magnetic shell. The spin polarization of the current increases with distance from the channel entrance until spin-flip processes become effective. Thus, in contrast to the spin-filter scheme, the spin polarization in a spin-guide can exceed significantly the spin polarization of the current in the magnetic material which surrounds the non-magnetic channel.

In general, a spin-guide may generate an almost fully (100%) spin-polarized current even if the magnetic material which is used is not fully polarized. Even a small difference between the spin-up and spin-down conductivities in the magnetic material ($\sigma_{M\uparrow}/\sigma_{M\downarrow} < 1$ in our case) would lead to a depletion of the current states in the non-magnetic channel, with spin-down electrons being affected over shorter distances from the channel entrance than the spin-up electrons. In this case, the spin polarization will be determined by the difference of the quantities in the exponent of Eq. (11); consequently, the spin polarization of the current will tend to approach the limiting value (i.e. 100%) further into the channel.

At this stage, certain issues pertaining to the operation of the proposed spin-guide scheme warrant comment. We begin by noting that though the spin polarization is expected to remain high even when a non-ideal magnetic material is used, the total current in the channel will de-
crease with increasing channel length (see Eqs. 1, 8 and 5). This occurs because both the spin-up and spin-down electrons can leave the channel and thus reach the grounded contact. In this context we note that there are ways to reduce significantly the loss of current, thus allowing its transmission over a large distance. To this end one may wish to use an alternation of the grounded and ungrounded sections of the magnetic shell along the spin-guide. Alternatively, one may reduce the loss of total current in the channel by creating tunnel barriers between the non-magnetic channel and the magnetic shell; such barriers, however, will retard the exit of both electron polarizations to the grounded boundaries.

The polarizing ability of a spin-guide is limited only by the spin-flip processes. Here we should note, that the role of spin-flip processes both in a non-magnetic channel and in the magnetic region of the spin-guide, differs in an essential way from the role of spin-flip processes in a spin-filter. First, let us consider spin-flip processes in the non-magnetic semiconductor only. In contrast to the spin-filter scheme, while spin-flip limits the spin-polarization in the spin-guide, it can not destroy it fully. Moreover, the spin polarization remains a constant and high enough, as follows from Eq.(2), for arbitrarily large distance from the entrance.

Next we consider the role of spin-flip in the magnetic shell of a spin-guide. Generally speaking, the exit of electrons with a spin “parallel” to that in the magnetic region (spin-down in our case), from the non-magnetic channel into the magnetic surroundings (as a result of their Brownian motion) is a harmless useful process. It is obvious that spin-flip scattering of these electrons will not reduce the spin polarization in the non-magnetic channel. However, spin polarization will be reduced due to the exit from the channel of spin-up electrons. They could change the spin polarization due to spin-flip scattering in the magnetic region and, subsequently, they could return back in the non-magnetic channel. The spin-flip probability could be decreased by reducing the width of the magnetic region; this method of bringing about a decrease in the spin-flip probability is not possible for the spin-filter scheme. In fact if the magnetic shell width is less than \( \lambda_M \), the sources of nonequilibrium spin concentration at the entrance and the exit of the current in the magnetic region will mutually cancel each other, and the polarizing ability of the magnetic filter will decrease significantly, as observed experimentally\textsuperscript{11,12}. Furthermore, the high conductivity of the magnetic material in the spin-guide scheme does not increase the spin-flip probability because it speeds up the transport of electrons to the ground contact. Unlike the spin-filter scheme, spin polarization in the spin-guide, \( \alpha \), does not depend on the ratio \( \sigma_{M\uparrow}/\sigma_{N\uparrow} \). We recall that the large ratio \( \sigma_{M\uparrow}/\sigma_{N\uparrow} \), characteristic of the spin-filter “ferromagnetic metal-semiconductor” interface\textsuperscript{5,6,7}, is one of the main reasons for the low degree of spin polarization in this scheme\textsuperscript{8}. If the spin-guide is used with tunnel barriers between the non-magnetic channel and the magnetic shell and with an additional applied voltage to the tunnel barrier, then the barriers act as additional filters. Those electrons that crossed the barriers and underwent an inelastic scattering in the magnetic shell are not capable to return back into the non-magnetic channel. Consequently, the spin-flip processes in the magnetic region will affect the current and thus the spin polarization in the channel to a lesser extent.

Thus, there is a physical difference in the role of spin-flip between the two schemes. Spin-flip scattering in the magnetic shell of spin-guide leads mainly to a reduction of the total current, while the spin polarization may change only by a small amount. The reverse situation occurs in the spin-filter scheme, i.e. the spin-flip processes maintain the total current as a constant but cause a significant reduction in the spin-polarization, as discussed in Section I.

As evident from the above, the spin polarization of the current in a spin-guide depends significantly both on it’s length and on the widths of the channel and the magnetic shell. Hence, by varying these parameters it should be possible to readily change and control the degree of current polarization at the channel exit. In the following we provide some quantitative estimates concerning the degree of spin polarization that may be achieved in the spin-guide scheme.

Among the most promising candidates for the magnetic shell material in a spin-guide are II-VI-DMS compounds (like a \( Be_5,Mn_2,Zn_{1-\gamma}S\)) or halfmetals where one of the spin subbands can be fully pinned. Assuming a non-magnetic channel with \( \lambda_N = 1.5 \mu m \) (a case that is far from being optimal), \( = 0.3 \mu m \) and \( d = 0.4 \mu m \), we obtain according to the Eq.(9) a current spin polarization in the channel \( \alpha = 100\% \) (within a 1% accuracy) for an arbitrary distance from the entrance; the current amplitude will decay with \( \lambda_N \), according to Eq. 9. Even for DMS compounds which are not fully polarized, employed as the magnetic region, we can achieve a high spin polarization. For example, taking \( Zn_{0.99}Be_{0.03}Se \) as a NMS (non-magnetic semiconductor) channel material, in contact with a 45% polarized \( Zn_{0.89}Be_{0.05}Mn_{0.96}Se \) as a DMS shell with a spin-flip length \( \lambda \approx 20 \mu m \), yields according to Eqs. 15 and 14 a 95% spin polarization for a width of the magnetic shell \( (d - w) \approx 10nm \); for \( (d - w) \approx 50nm \) we obtain a spin polarization \( \alpha \approx 17\% \).

Finally, a very high degree of spin polarization of the current may be achieved even if a ferromagnetic metal shell (e.g., Ni, Fe or Py) is used in the spin-guide. Here one should employ thin ferromagnetic films with a thickness that is less than the diffusion spin-flip length \( \lambda_M \); this is feasible even when \( \lambda_M \) is about several tens of nanometers. Thus, when the ballistic regime is reached in the magnetic region, f.e. \( \lambda_M \approx 20nm \), with \( \gamma \approx 0.6 \), \( d - w \approx 8nm \) and \( \lambda_N \approx 1.5 \mu m \), one obtains from Eq. 15 that \( \alpha \approx 100\% \), within the accuracy of the model. For rather thick film, such that the diffusion regime is reached, with \( d = 60nm \), \( w = 0.7d \), \( \lambda_M = 20nm \), we obtain from Eq. 14 \( \alpha \approx 0.97\% \).

From the above we conclude that the spin-guide
scheme works most effectively if both the widths of the non-magnetic channel and the magnetic shell are taken to be much less than the corresponding spin-flip length. In view of realistic spin-flip length scales, we suggest that nano-scale structures would be most appropriate for fabrication of spin-guide devices; for example through the use of nanowires and layers of nano-widths dimensions.

VI. SUMMARY

In this paper a spin-guide has been proposed as a new type of source and a long-distance transmission medium of electric currents with a high degree of spin polarization. We have shown that spin-guide enhances significantly the capabilities for generation and manipulation of spin-polarized currents. The main features of the spin-guide scheme which make it a most promising tool for creation and transport of spin-polarized currents in non-magnetic semiconductors, may be summarized as follows:

(i) In a spin-guide, a permanent withdrawal of electrons of one spin polarization leads to an increase in the other spin polarization, thus allowing to achieve a high degree of spin-polarization of the current, considerably exceeding the degree polarization in the magnetic shell.

(ii) The propagation length of a spin-polarized current in a non-magnetic channel of a spin-guide may exceed significantly the spin-flip length in the material.

(iii) Spin-flip processes in the magnetic shell restrict the peak value of the spin polarization of the current in a spin-guide to a much lesser degree than in the spin-filter scheme.

(iv) Through the use of the spin-drag scheme (or by combining the spin-guide and spin-filter schemes) with electrostatic gates on the channel exits, it may be possible to control the spin polarization of the current and to switch it easily and promptly, without magnetization reversal of the magnetic shell.

(v) A very large magneto-resistance effect is predicted to occur, which should allow direct sensing and measurement of presence and degree of spin polarization.

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