Spin-guide source for the generation of highly spin-polarized currents

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A ‘‘spin-guide’’ source for generation of electric currents with a high degree of spin polarization, which allows long-distance transmission of the spin polarization, is proposed. In the spin-guide scheme, a nonmagnetic conducting channel is interfaced or surrounded by a grounded magnetic shell that transmits electrons with a particular spin direction preferentially, resulting in net polarization of the current flowing through the channel parallel to the interface. It is argued that this method is more effective than spin-filter-like schemes 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 that 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 spintronic devices.

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I. INTRODUCTION

Recently there has been a growing interest in spintronic devices,[1–6] 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 nonmagnetic 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 nonmagnetic conducting material; we will refer to this idea as the ‘‘spin-filter’’ scheme.[7,8] 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[9–12]). There are two main reasons for this inefficiency:[13,14] (i) the spin relaxation time is much smaller in a ferromagnetic material than in a nonmagnetic one, and (ii) the conductivity of the ferromagnetic metal injector is much higher than the conductivity of the semiconductors that are usually used as nonmagnetic 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 a number of additional essential limitations inherent to the spin-filter scheme. First, the spin polarization of the injected current cannot exceed the spin polarization of the current in the magnetic material (serving as an injector). Second, the distance over which a significant degree of spin polarization may be maintained in a nonmagnetic material cannot 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[15] or the oblique Hanle effect technique[12]).

Recently, the spin-injection efficiency has been markedly increased;[16,17] indeed, by replacing the ferromagnetic metal by a dilute magnetic semiconductor (DMS), $Be_xMn_yZn_{1-x-y}Se$, a record degree of polarization (up to 90%) has been achieved.[16] 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,[12,18–21] address only one of the above-mentioned limitations, i.e., they only attempt to enhance the spin polarization of the injected current.

In this paper we propose a method for generation and transport of high spin-polarized currents. We term the proposed method a *spin-guide* scheme. The spin guide is based on a new interface configuration[22] that allows one to alleviate the aforementioned intrinsic limitations associated with

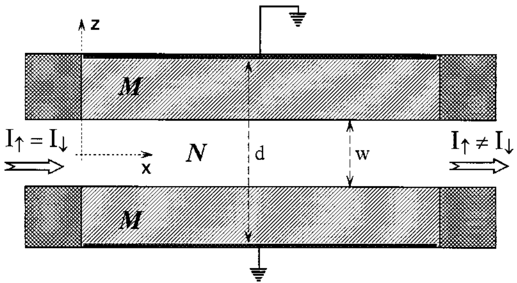

FIG. 1. Cross-sectional view of the spin-guide scheme. *w* is the width of the nonmagnetic channel (*N*), and *d* is the distance between the grounded contacts of the magnetic shell (*M*). The cross hatched regions indicate a dielectric material.

the spin-filter schemes. Under certain conditions a spin guide may generate an almost perfect (100%) spin-polarized current even when a magnet with a relatively low degree of spin polarization is used. Moreover, in the spin-guide scheme the spin polarization may be transmitted over large distances that exceed significantly the spin-flip length in nonmagnetic materials. Finally, spin guides allow easy detection and control of the spin polarization and, as discussed below, they may form the basis for creating fast spin-polarization switches.

The paper is organized as follows. In Sec. II we describe the basic idea underlying the spin-guide scheme and display the equations governing the process. Results of our study are given in Sec. III, for both a fully polarized (Sec. III A) as well as for a nonideal magnetic region (Sec. III B); a detailed derivation of the solutions and explicit expressions are given in the Appendix. In Sec. IV we introduce a spin-splitter scheme and discuss the magnetoresistance effect and its utilization for detection of the current spin polarization in a spin-guide device. Further discussion of our results can be found in Sec. V, and a summary is given in Sec. VI.

II. BASIC IDEA AND APPROACH

A spin guide is a system consisting of a nonmagnetic conducting channel (wire or strip) wrapped around by a grounded magnetic shell (see Fig. 1). Unlike the spin filter, electric current flows here parallel the interface, instead of being normal to it. The main idea is that nonequilibrium electrons with a particular spin polarization (e.g., polarization that coincides with the magnetization axis) leave the nonmagnetic channel preferentially to the magnetic material. The return of these electrons into the channel is prohibited because the outside magnetic shell boundaries are grounded. Consequently, a permanent outflow of nonequilibrium electrons with a definite spin polarization is obtained, and an excess of nonequilibrium electrons of the other spin polarization appears in the channel.[23] Note that the spin polarization of the current in the channel is opposite to the spin polarization of the current flowing in the surrounding magnetic shell, in contrast to the spin-filter geometry.

For the sake of specificity and simplicity, let us consider a flat configuration where the interface is a planar plate. We will also assume that the properties of the system remain constant in the *y* direction (i.e., normal to the plane of Fig. 1); the extensions to other geometries (e.g., a cylindrical wire) are rather straightforward. We will consider the diffusive transport regime, where the diffusion step lengths $l_{\uparrow,\downarrow}$ ($l_{\uparrow,\downarrow}$ are, respectively, the electron-impurity mean-free paths for the spin-up and spin-down electrons) 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 nonequilibrium parts of 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

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

where $\sigma_{\uparrow,\downarrow}$ are the corresponding conductivities. The spin transport, within the diffusive regime approximation, is described by the following equations (see Refs. 24, 25, and 13)

$$\mathrm{div}(\sigma_{\uparrow,\downarrow}\nabla\mu_{\uparrow,\downarrow}) = \frac{\Pi_0 e^2}{\tau_{\mathrm{sf}}}(\mu_{\uparrow,\downarrow}-\mu_{\downarrow,\uparrow}),$$
$$\Pi_0^{-1} = \Pi_\downarrow^{-1} + \Pi_\uparrow^{-1}, \tag{2}$$

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

Note that we can find the currents in the spin guide without separation of the electrochemical potential into the chemical (η) and electrical (φ) potential contributions, i.e., $\mu_{\uparrow,\downarrow} = \eta_{\uparrow,\downarrow} + e\varphi$. These potentials can be easy 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 its 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 $\mu_{\uparrow,\downarrow} = 0$ (on the boundaries). 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; here we note that an excess of the potential at the exit over the grounded boundaries is equivalent to an inefficient dissipation of energy into the ground.

Let an unpolarized current I be driven through the channel entrance. As shown in the Appendix, the most important characteristics of sufficiently long spin guides are insensitive to the type of boundary conditions that are imposed at the ends of the spin guide (in particular, on the magnetic shell, e.g., grounding or absence of current). Let the spin-up and spin-down current densities (per unit length in the y direction) at the channel entrance be expressed as $J_{\uparrow,\downarrow}=-e^{-1}\sigma_N\,\partial\mu_{\uparrow,\downarrow}/\partial x=I/(2w)$. We also assume that the conductivity in the nonmagnetic channel σ_N is spin independent and that the conductivity in each region is constant.

For the spin-guide model described above, the diffusion equation (2) can be solved through a separation of variables for the functions μ_+ and μ_- defined as $\mu_+=(\sigma_\uparrow\mu_\uparrow+\sigma_\downarrow\mu_\downarrow)/(\sigma_\uparrow+\sigma_\downarrow)$ and $\mu_-=\mu_\uparrow-\mu_\downarrow$. We will seek solutions for the functions $\mu_\pm$ expressed as products of two functions, one depending on the x variable and the other depending on the z coordinate (and on the discrete indices $\pm$). Owing to the symmetry of the system and the boundary conditions at $z=\pm d/2$, we obtain the following special solutions of Eqs. (2):

$$\mu_\pm=e^{-kx}f_\pm(z), \tag{3}$$

where the functions $f_\pm$ are given by

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

$$f_-=\begin{cases}C\cos \kappa_N z, & |z|<w/2\\ D\sin \kappa_M(d/2-z), & |z|>w/2\end{cases} \tag{4}$$

and

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

where $\lambda_{M,N}$ is the diffusion length in the magnetic (M) and nonmagnetic (N) regions, respectively. Matching the functions $\mu_{\uparrow,\downarrow}$ and the currents (i.e., the derivatives $\sigma_{\uparrow,\downarrow}\partial\mu_{\uparrow,\downarrow}/\partial z$) at $z=\pm w/2$, we obtain Eqs. (A7) for the coefficients A, B, C, and D. Equating the determinant of this system of equations to zero, we get Eq. (A9), whose solution allows us to determine the possible values of the damping factor k. The complete solution that satisfies all the boundary conditions may be written as a superposition of the functions given in Eq. (3) [see the Appendix, Eq. (A3)]. It is shown in the Appendix that for a long enough spin guide ($L\gg k_{\rm min}^{-1}$, where L is the spin-guide length and $k_{\rm min}$ is the smallest allowed positive value of the damping factor k), the solution reduces to a much simpler form at distances $x\gg k_{\rm min}^{-1}$ from the entrance to the channel. In this case, up to exponentially small values, we may keep only two terms in the sum given in Eq. (A3) with $k=\pm k_{\rm min}$ [see Eq. (A12)]. If we consider the region that is also far away from the exit ($L-x>k_{\rm min}^{-1}$), the main contribution to the solution is given by the term that decreases exponentially with the x coordinate, i.e., $\mu_{\uparrow,\downarrow}\propto\exp(-k_{\rm min}x)$. The physical meaning of $k_{\rm min}^{-1}$ is quite obvious: it is the distance in the x direction that an electron will traverse diffusively before it will reach the grounded contact. It is worth noting that the degree of spin polarization of the current in this case ($x\gg k_{\rm min}^{-1}$) does not depend on the x coordinate and on the type of the boundary conditions [see Appendix, Eq. (A13)].

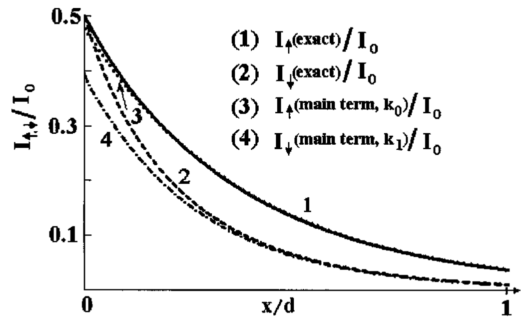

FIG. 2. Dependence of the spin-up and spin-down currents $I_{\uparrow\downarrow}$ (in units of I_0, where I_0 is the total current at the channel entrance) on the coordinate along the spin guide (x normalized by the channel width d): the curves labeled 1 and 2 are calculated from the exact solution given by Eq. (A10) for $I_{\uparrow,\downarrow}$, respectively. Curve 3 is the contribution to the current $I_\uparrow$ from only the first term (the main contribution) of the sum in Eq. (A10) with $k_0=k_{\rm min}$, and curve 4 is the contribution to the current $I_\downarrow$ from only the second term (the main contribution) of the sum in Eq. (A10) with k_1. In the calculations we used $\sigma_{M\uparrow}/\sigma_{M\downarrow}=0.3$, $\sigma_{M\downarrow}/\sigma_N=1.8$, $w/d=0.5$, $L=10d$, $w/\lambda_N=0.166$, $(d-w)/(2\lambda_M)=0.25$.

Let us consider next another type of solution that is valid for distances from the entrance where spin-flip processes have not yet occurred. In the absence of spin flip Eqs. (2) for $\mu_\uparrow$ and $\mu_\downarrow$ become independent and a separation of variables can be accomplished separately for each potential. Thus, we have

$$\mu_{\uparrow,\downarrow}=e^{-kx}_{\uparrow,\downarrow}f_{\uparrow,\downarrow}, \tag{5a}$$

with

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

$$f_{\uparrow,\downarrow}=B_{\uparrow,\downarrow}\sin[k_{\uparrow,\downarrow}(d/2-z)]\quad \text{at}\quad |z|>w/2. \tag{5b}$$

From the matching conditions at $z=\pm w/2$ the following transcendental equations are obtained for the damping factors $k_{\uparrow,\downarrow}$:

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

To illustrate the behavior of the current in the channel we computed the x dependencies of the currents $I_{\uparrow,\downarrow}$ using the exact solution [see Eq. (A3)] for a given constant current density in the channel entrance, and for $\mu_{\uparrow,\downarrow}=0$ at the channel exit. The results of these calculations are displayed in Fig. 2 (curves labeled 1 and 2). We present also the contribution of the special solution with $k\cong k_{\rm min}=0.0129\times10^6\ {\rm cm}^{-1}$ (curve 3) to the current $I_\uparrow$, and the contribution of the special solution with $k\cong k_1=0.0187\times10^6\ {\rm cm}^{-1}$

$>k_{\min}$ [where k_1 is the next solution of Eq. (A9)] to the current $I_\downarrow$ (curve 4). For certain values of the diffusion lengths, $\lambda_{N,M}$, which are large enough compared to w and $(d-w)/2$, we obtain $k_{\min}\cong k_\uparrow$ and $k_1\cong k_\downarrow$, where $k_\uparrow$ and $k_\downarrow$ are the smallest allowed positive values of the solutions of Eq. (6). It is evident from Fig. 2 that in the region $x \geqslant d/2$ the currents $I_{\uparrow,\downarrow}$ are well described by the approximate dependencies that follow from Eq. (5); see the next section and the Appendix for details of the domain of applicability of the type of solution given in Eq. (5a). 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 only spin-down electrons can cross the magnetic shell, i.e., $\sigma_{M\uparrow}=0$.

We consider the case when the spin polarization of the current in the channel is high enough, i.e., the width of the nonmagnetic channel w is less than the spin-flip length λ_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 nonmagnetic semiconductors, i.e., up to 100 μm.[26,27] For sufficiently short distances from the entrance, so that no spin-flip processes have occurred, the current $I_\uparrow$ 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, $I_\downarrow$, will decrease exponentially with distance from the entrance into the channel, i.e., $I_\downarrow \propto \exp(-k_\downarrow x)$.

According to Eq. (6) we have $k_\uparrow=0$ (since $\sigma_{M\uparrow}=0$), and $k_\downarrow$ will depend on the ratio $\sigma_{M\downarrow}/\sigma_N$. Accordingly, for $\sigma_{M\downarrow}=\sigma_N$ the damping factor $k_\downarrow=\pi/d$. If the conductivity of the magnetic shell is much higher than that of the nonmagnetic channel, i.e., when $\sigma_{M\downarrow}\gg\sigma_N$, the damping factor takes the value $k_\downarrow=\min\{\pi/w,\pi/(d-w)\}$. Consequently, the spin polarization of the current tends exponentially to unity with increasing x, that is,

$$\alpha=\frac{I_\uparrow-I_\downarrow}{I_\uparrow+I_\downarrow}\approx 1-a e^{-k_\downarrow x}. \tag{7}$$

Here, we should note [see also the Appendix, Eq. (A15) and the discussion therein] that to calculate the preexponential coefficient a in Eq. (7) we have to state the boundary conditions at the entrance and exit of the spin guide. Thus, Eq. (7) yields only the exponential approach to the ideal spin polarization as we move away from the channel entrance. It is obvious, however, that if we introduce an unpolarized current into the spin guide, then $a\approx 1$: $I_\uparrow(x)=I_0/2$ and $I_\downarrow(x)\approx(I_0/2)\exp(-k_\downarrow x)$. For example, as shown in Fig. 2, at $x\geqslant d/2$ we have $I_\downarrow(x)=0.8(I_0/2)\exp(-k_1 x)$, $k_1\cong k_\downarrow$.

We turn now to an analysis of the role of spin-flip processes in the nonmagnetic channel. We will be interested mostly in the case of comparatively rare spin-flip scattering processes $\lambda_N k_\downarrow \gg 1$, when a high level of the current spin polarization can be achieved. The inequality $k_{\min} d \ll 1$ follows from the previous inequality (if $\sigma_N/\sigma_{M\downarrow}<1$, then both are equivalent), and we can replace all tangents in Eq. (A9) by their arguments and also neglect the term $2\sigma_N/\sigma_{Mt}\tan(t_N')\tan(t_M')$ as compared to unity. Consequently, taking into account that $\sigma_{M\uparrow}=0$ and $\sigma_{Mt}=\sigma_{M\downarrow}\equiv\sigma_M$, we obtain from Eq. (A9)

$$k_{\min}^{-1}\cong\sqrt{2}\lambda_N. \tag{8}$$

Using Eqs. (3), (4), (A1), and (A13), we obtain to the same accuracy

$$\mu_{\uparrow,\downarrow}=f_{\uparrow,\downarrow}e^{-x/2\sqrt{\lambda_N}},$$

$$f_\uparrow\cong\text{const}\cong A,\quad f_\downarrow\cong\frac{Aw}{16\lambda_N^2}\left[w+2\frac{\sigma_N}{\sigma_M}(d-w)-4\frac{z^2}{w}\right]$$

$$\text{at } |z|<\frac{w}{2}, \tag{9}$$

$$f_\downarrow\cong\frac{Aw}{8\lambda_N^2}\frac{\sigma_N}{\sigma_M}\left[d-w-2\left(z-\frac{w}{2}\right)\right]\quad\text{at } |z|>\frac{w}{2},$$

$$1-\alpha=\frac{w}{12\lambda_N^2}\left[w+(3d-2w)\frac{\sigma_N}{\sigma_M}\right].$$

Thus, the exponential decrease of $1-\alpha$ [recall Eq. (7)] is bounded below by the value given in Eq. (9). Consequently, the spin polarization remains constant and sufficiently high for all distances away from the entrance. Both the spin-up and spin-down currents $I_{\uparrow,\downarrow}$ decay exponentially with the same damping factor k. The total current will decay as the spin-up electrons succeed in leaving the nonmagnetic channel due to spin-flip processes.

B. A nonideal magnetic region

In this section, we discuss the situation when the magnetic shell that interfaces with the conducting nonmagnetic 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 nonmagnetic 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. (5), the spin polarization of the current in the channel will tend exponentially to unity,

$$\alpha \approx 1 - a e^{-(k_\downarrow - k_\uparrow)x}. \tag{11}$$

Moreover, from Eqs. (10) and (6) we have $k_\downarrow > k_\uparrow$. As shown in the preceding section, for $\sigma_{M\uparrow} \gg \sigma_N$ we obtain $k_\downarrow^{-1} \ll d$, and for $\sigma_{M\uparrow} \ll \sigma_N$ the spin-up current decays on a length scale that is large compared to d, that is [to obtain the following formula we replace all tangents in Eq. (6) by their arguments, i.e., $k_\uparrow w/2$ and $k_\uparrow(d-w)/2$],

$$k_\uparrow \cong 2\sqrt{\frac{\sigma_{M\uparrow}}{\sigma_N w(d-w)}} \quad \text{for} \quad k_\uparrow d \ll 1. \tag{12}$$

We consider now the role of spin-flip processes in the magnetic shell. As discussed above, the exponential decrease of the currents $I_{\uparrow,\downarrow}$ (as a function of the distance away from the channel entrance) that occurs 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-spin 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 Eq. (6). In other words, $k=k_\uparrow$, where $k_\uparrow$ is determined from Eq. (12) if $\sigma_{M\uparrow} \ll \sigma_N$, and $k_\uparrow \approx d^{-1}$ if $\sigma_{M\uparrow}$ is greater than or of the order of σ_N. The reason is that the overall damping rate is governed by the spin component that takes more time to reach the grounded boundaries. To calculate the spin polarization of the current far away from the distance from the entrance of the spin guide we have to find the higher-order correction to k. To this aim we expand Eq. (A9) in a series with the small parameter $\delta(d-w)$ (where we define $\delta \equiv k - \kappa_M$, in order to focus on the contribution of spin-flip processes) and keep terms up to (and including) the second-order term. Substituting this expansion of k into Eq. (A13) [note that if we use instead the first approximation $k=k_\uparrow$ in Eq. (A13), we obtain, obviously, $\alpha=1$], yields

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

In conjunction with Eq. (6) for $k=k_\uparrow$, Eq. (13) determines a high degree of the spin polarization, i.e.,

$$1-\alpha \approx \gamma(d-w)^2/\lambda_M^2(1-\gamma^2) \ll 1. \tag{14}$$

We note that this inequality may be violated if γ [see Eq. (10)] is too close to unity, because in this case the conductivities in the magnetic material of the spin-up and spin-down electrons approach each other, and the magnetic material does not act as a "spin separator." Finally, the potentials $\mu_\pm$ can be found directly from Eqs. (4), (A8), (A14), and (13).

In Fig. 3 the curve labeled 1 depicts the x dependence of the spin-polarization level, calculated from the exact expression [see Eq. (A11)] with $\sigma_{M\uparrow}/\sigma_{M\downarrow}=0.3$, $\sigma_{M\downarrow}/\sigma_N=1.8$, $w/d=0.5$, $L=10d$, $w/\lambda_N=0.166$, and $(d-w)/2\lambda_M=0.25$. The curve labeled 2 is calculated in the approximation that was used for obtaining Eqs. (11) and (13) and the subsequent asymptotic expressions; we keep only the first and second terms of the sum [see Eq. (A3)], and the coefficients c_0' and c_1' [see Eq. (A6)] are chosen in such a way that the current is unpolarized at the entrance. Before reaching the saturation value curve 2 corresponds to Eq. (11) with $a \approx 1$; if spin-flip processes are rare, then the dominant contribution to $I_\uparrow$ (before saturation) is from the exponential term with $k_{\min}=k_0 \cong k_\uparrow$, and the dominant contribution to $I_\downarrow$ is from the exponential with $k_1 \cong k_\downarrow$. The curve labeled 2 achieves the saturation value when the contribution of the term with k_0 becomes dominant for both $I_\uparrow$ and $I_\downarrow$. Thus, Fig. 3 demonstrates the validity of our asymptotic approach (even near the entrance to the spin guide) and supports the physical picture when the spin-polarization level reaches exponentially the constant value determined by the spin-flip processes.

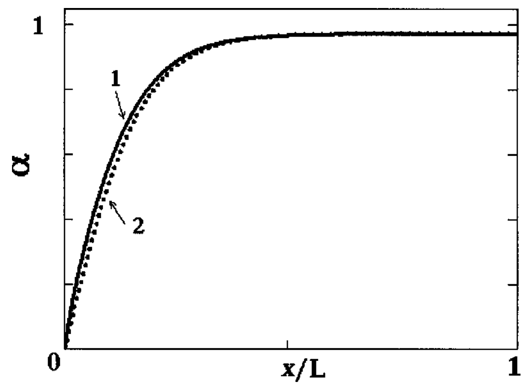

FIG. 3. The dependence of the degree of spin polarization of the current (α) on the coordinate along the spin guide (x normalized by the length of the spin guide L). The curve labeled 1 is calculated form the exact solution given in Eq. (A11) with the same spin guide parameters as in Fig. 2. Curve 2 is calculated using an approximate solution to Eq. (A11); see text.

From the above considerations we conclude 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 λ. There are additional essential differences between the two schemes. Unlike the spin-filter scheme, the spin polarization (α) in the spin guide does not depend on the conductivity ratio $\sigma_{M\uparrow}/\sigma_N$. Moreover, as may be seen from Eqs. (11) and (13) the degree of spin polarization in the nonmagnetic channel can exceed significantly the degree of spin polarization in the magnetic material.

In the case $\lambda_M \gg d-w$, a significant high degree of spin polarization may be achieved when the condition $\gamma(d-w) \ll \lambda_M$ is fulfilled. Let us neglect in Eq. (A9) the term $(2\sigma_N/\sigma_{Mt})\tan(t_N)\tan(t_M)$ compared to unity [as seen from Eq. (A13) this approximation is equivalent to the statement that the spin-polarization is indeed sufficiently high]. As a result we obtain the following equation for k:

$$k\tan(t_N)\tan(t_M') = \kappa_M \frac{\sigma_{M\uparrow}}{\sigma_N}. \tag{15a}$$

At $\lambda_M \ll d-w$ this equation transforms into

$$k\lambda_M \tan(t_N) = \frac{\sigma_{M\uparrow}}{\sigma_N}, \tag{15b}$$

and if $k(d-w) \ll 1$ we have from Eq. (15b)

$$k \cong \sqrt{\frac{2\sigma_{M\uparrow}}{\sigma_N w \lambda_M}}. \tag{15c}$$

Combining Eqs. (15a) and (A13) yields

$$1-\alpha = 2\gamma \frac{\tan[k(d-w)/2]}{k\lambda_M}. \tag{16}$$

It follows from Eq. (16) that the spin-polarization level is indeed high enough: that is, $1-\alpha$ is of the order of $\gamma(d-w)/\lambda_M$ [except when $k \approx \pi/(d-w)$]. If the magnetic shell is too thick, i.e., when $\gamma(d-w)/\lambda_M \gg 1$, the spin polarization of the current is low.

As mentioned earlier, to increase the spin polarization one should decrease the width of the magnetic region. To this end, the ballistic regime when $d-w \ll (l_{M\uparrow}, l^{\mathrm{sf}}_{\uparrow,\downarrow})$ is most favorable. A calculation that goes beyond the framework of the diffusion approach yields in the ballistic limit the following result:

$$1-\alpha \approx \gamma \frac{l_{M\downarrow}(d-w)}{\lambda_M} \ln \frac{1}{(d-w)(l_{M\downarrow}\lambda_M^{-2} + l_{M\downarrow}^{-1})}. \tag{17}$$

Here the ratio of the lengths in the coefficient in front of the logarithm is the probability of a spin flip to occur when an electron crosses the magnetic shell [cf. Eq. (16)]. The logarithmic factor in this formula reflects an enhancement of the spin-flip probability for electrons grazing along a magnetic layer.

Analyzing the most favorable combinations of the spin-guide parameters, we note the following: (i) a high conductivity of the magnetic shell does not reduce the high degree of the spin polarization of the current, and (ii) decreasing the thickness of the magnetic shell increases the polarization. These statements are valid at a distance from the entrance where the constant (saturated) value of the spin polarization is attained [i.e., where the potentials are described by Eq. (A12)]. Note however, that, as can be seen from Eqs. (6) and (11), this distance increases with increasing conductivity of the magnetic shell and/or when its thickness is reduced. Indeed, if $\sigma_{M\uparrow,\downarrow} \gg \sigma_N$ and $w > d-w$, we obtain from Eq. (6) for the smallest allowed values $k_{\uparrow,\downarrow}$

$$k_{\uparrow,\downarrow} w \approx \pi - 2\frac{\sigma_N}{\sigma_{M\uparrow,\downarrow}} \tan\left(\frac{\pi(d-w)}{2w}\right). \tag{18}$$

In other words, the difference $k_\downarrow - k_\uparrow$ is very small. In Sec. V below, we propose certain ways for increasing the relative magnetic shell resistance that serve to reduce the spin-guide length over which the spin polarization of the current is created and that consequently reduce the loss of total current in the channel.

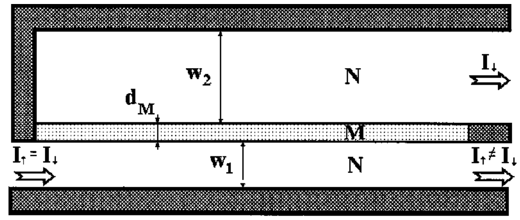

FIG. 4. The spin-splitter scheme. The nonmagnetic (N) channels 1 and 2 are of widths w_1 and w_2, respectively. The width of the magnetic (M) interlayer is d_M, and the cross-hatched regions indicate a dielectric material.

IV. SPECIFIC EFFECTS AND POSSIBLE EXPERIMENTAL REALIZATIONS

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

A. Spin splitter

We begin with a discussion of a scheme alternative to that discussed above, for obtaining the spin-guide effect on the polarization of the electric current. This alternative scheme is based on a spin-splitter effect that can be realized in a geometry of two semiconductor channels separated by a magnetic interlayer (see Fig. 4).

Let a nonpolarized 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., $|\alpha_2| = 1$ (in the schematic shown in Fig. 4 we have assumed that the magnetic interlayer transmits selectively spin-down electrons). At the same time, a polarization α_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 d_M is taken to be less than the widths of the nonmagnetic channels, w_1 and w_2, and for $L \gg w_1, w_2$ (where L is the channel length), we obtain

$$\alpha_1 = \frac{w_2}{w_2 + 2w_1}. \tag{19}$$

This formula follows from the simple fact that equal current densities for the particular spin component are established on a length scale that exceeds the current penetration length into the second channel (of the order of w_2 when $\sigma_N/w_2 \leq \sigma_M/d_M$).

The polarization of the currents in channels 1 and 2 is opposite to each other, and the total current in the two channels is unpolarized. In Fig. 4 the current in channel 2 is polarized in the spin-down direction, the current in channel 1 is preferentially polarized in the spin-up direction. 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., a fully polarized current $I_\uparrow = I_0/2$ will appear in channel 1 with an equal current but with opposite polarization flowing in channel 2. In the derivation of

Eq. (19) 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 I_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 the conductivity ratio $\gamma \ll 1$, the spin polarization determined by Eq. (19) is maintained for distances $L < R$, where $R = \min\{(rw\sigma_N/\sigma_{M\uparrow})^{1/2}, \lambda_N\}$ and $r = \min\{d_M, \lambda_M, l_{M\uparrow}\}$; note that the estimate R, reflects the dependence of the spin-depolarization on the spin-flip processes and on the transverse transport out of channel 1 of both spin directions (in proportion to the conductivity ratio). 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 nonmagnetic channels, i.e., $d_M > w_1, w_2$, then the Sharvin resistances[28] of the exit constrictions 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-splitter scheme with electrostatic gating. In the spin-splitter scheme shown in Fig. 4 the current at the exit of the first channel is spin polarized preferentially in the up direction [see Eq. (19)] and the polarization in the second channel is in the opposite direction. Blocking the exit of the second channel by an electrostatic gate and at the same time allowing transport of electrons through the channel to the left results in currents of opposite spin polarizations flowing in opposite directions. If we reverse the roles of channels 1 and 2 in the above description the sense of the polarizations in the two x directions will be reversed. Consequently, switching can be achieved by alternating between these two possibilities. Note that this switching may be operated at a fast rate, since it involves electrostatic gating, and it does not require switching the magnetization of the magnetic material. On the other hand, in the spin-filter scheme fast switching of the spin polarization of the current cannot be achieved 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.

Finally we remark on another hybrid device that combines the spin guide with a spin-filter-like scheme. This device is obtained if current is allowed to be emitted from the exit (x direction) of the magnetic shell in addition to the current emitted by the nonmagnetic channel of a spin guide (see Fig. 1). In this case currents of opposite polarizations will be emitted from the device.

B. Giant magnetoresistance and methods of detection of the current spin polarization

In this section we discuss certain physical effects that could be utilized for the detection of the spin polarization of the current. 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 nonmagnetic channel (to an essentially vanishing value) upon switching-off of the magnetizing field. That is, in the absence of a magnetic field electrons with both spin directions leave the channel through the DMS shell, resulting in a decrease, and eventual vanishing, of the current in the channel. The reverse occurs when the magnetizing field is switched on, i.e., a current appears in the channel, since under this condition only electrons with one of the spin directions (e.g., spin down) leave the channel, while electrons with the other spin direction remain in the channel and contribute to the current. Switching-off of the magnetic field leads to an increase of the damping factor of the current from the value $k_{\min}$ [in the case of an ideal magnetic material shell $k_{\min} \approx (\lambda_N \sqrt{2})^{-1}$; see Eqs. (8)] up to k_{UM} which depends on the ratio of the conductivities of the unmagnetized DMS shell, σ_{UM}, and that of the nonmagnetic channel σ_N. The damping factor k_{UM} can be determined (following Eq. (A9)) by the equation

$$\tan(k_{\mathrm{UM}} w/2) \tan[k_{\mathrm{UM}}(d-w)/2)] = \sigma_{\mathrm{UM}}/\sigma_N. \quad (20)$$

In the case when $\sigma_{\mathrm{UM}} \approx \sigma_N$, we have $k_{\mathrm{UM}} \approx \pi/d$. For the spin-guide parameters indicated in Fig. 2 the current changes at the exit of the spin guide by more than 4 orders of magnitude upon on-off switching of the external magnetic field. This remarkable effect is caused by the fact that the disappearance of all of the nonequilibrium electrons at the grounded boundaries is faster then the rate of their arrival to the channel exit. This effect may result in a significant change in the resistance of the device with magnetizing field, even larger then the giant magnetoresistance effect measured in the spin-filter scheme.[17,29]

If a ferromagnetic material is used to interface with the nonmagnetic channel (instead of a DMS) a giant magnetoresistance effect may also be observed when the applied magnetic field switches the magnetization direction in the magnetic layers [above and below the nonmagnetic channel (see Fig. 1)] such that they transform from being parallel to each other to having opposite magnetization directions. If the upper and lower magnetic layers have the *same* magnetization direction then there is a current at the channel exit, since electrons with one of the spin directions leave the channel preferentially through the magnetic material that interfaces with it. However, if the magnetization direction of the upper and the lower layers are opposite to each other, then the current in the channel will essentially vanish, since both up and down electrons will leave the channel. Therefore, by changing the applied magnetic field we may change the resistance of the device; we note that the field may be applied in different directions to the upper and lower layers.

Note that the aforementioned magnetoresistance effects are related to the spin polarization of the current in the nonmagnetic channel and they permit detection of the spin polarization of the current in it. An alternative way, based on the spin-guide scheme, to detect the spin polarization may be realized by blocking a nonmagnetic channel far from the entry and exit by an electrostatic gate, as shown schematically in Fig. 5. The most significant changes in the resistance may be observed in a spin guide with a fully polarized magnetic shell under blocking conditions of the nonmagnetic channel. If the channel is electrostatically blocked, then the

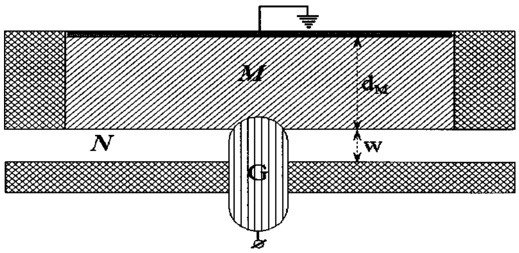

FIG. 5. Schematic description of the experiment with an electrostatic blocking of the nonmagnetic channel in a spin guide. G is an electrostatic blocking gate, d_M and w are the widths of the magnetic (M) and nonmagnetic (N) materials, and the crossed-hatched regions indicate a dielectric material.

finite conduction of the spin guide is due to the spin-down electrons that circumvent the blocked part of the channel by passing through the magnetized shell. As a result the net increase of the total resistance of the device is proportional to $(1-\alpha)^{-2}$, where α is the degree of spin polarization of the current in the nonmagnetic unblocked channel; we recall that $(1-\alpha)/2$ is the fraction of current due to spin-down electrons.

V. DISCUSSION

The main operational principle of a spin guide is the removal of one of the spin components of the 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 that surrounds the nonmagnetic channel. In general, a spin guide may generate an almost fully (100%) spin-polarized current even if the magnetic material that 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 current states in the nonmagnetic channel, with spin-down electrons (in our example) 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 nonideal magnetic material is used, the total current in the channel will decrease with increasing channel length [see Eqs. (1), (3), and (5a)]. The total transverse resistance of the spin-guide device (see Fig. 1), related to the loss of electrons that dissipate to the ground through the magnetic shell, consists of the transverse resistance of the nonmagnetic channel and the resistance of the magnetic shell. The losses of the electric current are most significant when the electric resistance associated with the transverse nonmagnetic channel resistance, $R_N \propto w/\sigma_N$, exceeds greatly the resistance due to the passage of electrons to the ground through the magnetic shell, $R_{M\uparrow,\downarrow}\propto(d-w)/\sigma_{M\uparrow,\downarrow}$. As follows from Eqs. (11) and (18), the length scale on which a high constant spin polarization of the current is established [of the order of $dR_N\gamma(1-\gamma)R_{M\downarrow}$ (at $d-w \ll w$)], is of the order of $(k_\downarrow-k_\uparrow)^{-1}$.

At the same time, the total current decays on a distance scale of the order of d. Methods for reduction of the current losses may include (i) reduction of the channel width near the entrance aiming at reducing the channel resistance R_N there (a point-contact-like entrance); (ii) the use of a porous magnetic shell consisting of narrow magnetic wires (connecting the nonmagnetic channel to the ground) instead of a continuous shell, thus increasing the resistance of the magnetic shell R_M (in inverse relationship to the cross-sectional area of the wires); (iii) the employment of different nonmagnetic materials in the construction of a spin guide—one material with conductivity of the order of the conductivity of the magnetic shell near the entrance that operates as a ‘‘polarization device’’ (see discussion toward at the end of Sec. III), and afterwards a second material with a lower conductivity that operates as the ‘‘transportation channel.’’ (Additionally, one may use different magnetic materials—one with a low conductivity near the entrance that works as a ‘‘polarization device’’ and a second one with a higher conductivity that works as a ‘‘polarization-supported device.’’) Finally, if we insert a potential barrier between the nonmagnetic channel and the magnetic shell, it adds additional resistance, R_b, to R_M, which serves to reduce the current loss at the stage of formation of the high-level spin polarization. Increasing the resistance for electron transport through the magnetic shell and the barrier over the resistance R_N results in conditions where the current decay length $(k_{\min}\approx w^{-1}[R_N/(R_M+R_b)]^{1/2})$ may exceed the total width of the device d [see Eq. (12) and Fig. 1]. However, we note that decreasing $k_\downarrow$ leads to degradation of the spin polarization due to spin-flip scattering in the channel; according to Eq. (9) $1-\alpha$ is of the order of $(k_\downarrow\lambda_N)^{-2}$.

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 the nonmagnetic 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 nonmagnetic semiconductor only. In contrast to the spin-filter scheme, while the spin flip limits the spin polarization in the spin guide, it can not destroy it fully; the interfacing magnetic shell will maintain at all times a certain degree of nonequilibrium in the distribution of spin-up and spin-down electrons. Moreover, the spin polarization remains constant and high enough, as follows from Eq. (9), over an 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 nonmagnetic channel into the magnetic surroundings (as a result of their Brownian motion) is a process that contributes to the ability to achieve spin polarization of the current. It is obvious that spin-flip scattering of these electrons will not reduce the spin polarization in the nonmagnetic channel (note that if such a spin-flipped electron returns into the nonmagnetic channel, it actually increases the spin polarization in the channel since it is in the spin-up direction). However, the spin polarization will be reduced due to the exit of spin-up electrons from the channel. They could change the spin polarization due to spin-flip scattering in the magnetic region, and subsequently they could return back to the nonmagnetic 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 cannot be used for the spin-filter scheme. In fact, in the spin-filter scheme, if the width of the magnetic region is less than λ_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 is indeed observed experimentally.[16,17] 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 grounded contact. Unlike the spin-filter scheme, the spin polarization in the spin guide, α, 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,[9–12] is one of the main reasons for the low degree of spin polarization in this scheme.[13] If the spin guide is used with tunnel barriers between the nonmagnetic 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 of returning back into the nonmagnetic channel. Consequently, the spin-flip processes in the magnetic region will affect the spin polarization of the current in the channel to a lesser extent.

Thus, there is a physical difference in the role of spin-flip processes between the two schemes. Spin-flip scattering in the magnetic shell of the 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 a constant total current but cause a significant reduction in the spin polarization, as discussed in Sec. I.

As evident from the above, the spin polarization of the current in a spin guide depends in an important way both on the device 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 spin polarization of the current 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 (such as a $Be_xMn_yZn_{1-x-y}Se$) or half-metals where one of the spin subbands can be fully pinned. Assuming a nonmagnetic channel with $\lambda_N = 1.5\ \mu$m (a case that is far from being optimal), $w = 0.3\ \mu$m and $d = 0.4\ \mu$m, we obtain according to Eq. (9) a full spin polarization of the current in the channel ($\alpha = 100\%$, within a 1% accuracy), for an arbitrary distance from the entrance; the current amplitude will decay with λ_N, according to Eq. (8). Even when employing not fully polarized DMS compounds as the magnetic region, a high spin polarization may be achieved. For example, taking $Zn_{0.97}Be_{0.03}Se$ as a nonmagnetic semiconductor channel material, interfaced with a 45% polarized $Zn_{0.89}Be_{0.05}Mn_{0.06}Se$ as a DMS shell with a spin-flip length $\lambda \approx 20$ nm yields according to Eqs. (13) and (16) a 95% spin polarization for a width of the magnetic shell $d - w \leqslant 10$ nm; for $d - w \approx 50$ nm 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 λ_M; this is feasible even when λ_M is about several tens of nanometers. Thus, when the ballistic regime is reached in the magnetic region, e.g., $\lambda_M \approx 20$ nm,[30,31] with $\gamma \approx 0.6$, $d - w \approx 8$ nm, and $\lambda_N \approx 1.5\ \mu$m, one obtains from Eq. (17) $\alpha \approx 100\%$, within the accuracy of the model. For a rather thick film, such that the diffusion regime is reached, with $d = 60$ nm, $w = 0.7d$, $\lambda_M = 20$ nm, we obtain from Eq. (13) $\alpha \approx 97\%$.

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

VI. SUMMARY

In this paper a spin guide has been proposed as a source and a long-distance transmission medium of electric currents with a high degree of spin polarization. As discussed above, the proposed spin-guide scheme may enhance significantly the capabilities for generation and manipulation of spin-polarized currents. The main features of the spin-guide scheme that make it a most promising tool for creation and transport of spin-polarized currents in nonmagnetic semiconductors, may be summarized as follows.

(i) In a spin guide, a permanent withdrawal of electrons of one spin direction leads to a nonequilibrium distribution with a relatively increased fraction of electrons with the other spin direction. This allows us to achieve a high degree of spin polarization of the current that may exceed considerably the degree of polarization in the magnetic shell.

(ii) The propagation length of the spin-polarized current in the nonmagnetic 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-splitter scheme [or by combining the spin-guide and spin-filter schemes (see Sec. IV A)] with electrostatic gates at the exits, it may be possible to control the spin polarization of the current and to achieve fast switching action, without magnetization reversal of the magnetic shell.

(v) A very large magnetoresistance effect is predicted to occur (see Sec. IV B), which should allow direct detection of the spin polarization of the current flowing through the device.

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APPENDIX: EXACT SOLUTION OF EQ. (2) AND APPROXIMATIONS

Let us introduce the functions $f_{\uparrow,\downarrow}(\mu_{\uparrow,\downarrow}=f_{\uparrow,\downarrow}e^{-kx})$, which are related to the functions $f_\pm$ [see Eq. (3)] as

$$f_s=f_+ + s\,\frac{\sigma_{-s}}{\sigma_t}f_- \,,\sigma_t=\sum_s \sigma_s\,. \tag{A1}$$

Here and below we will use the indices $s=\pm 1$ to designate spin-up (↑) and spin-down (↓) components. According to Eq. (2) the functions f_s have to satisfy the following equations:

$$\frac{d}{dz}\left(\sigma_s\frac{d}{dz}f_s\right)=\frac{\Pi_0 e^2}{\tau_{sf}}(f_s-f_{-s})-k^2\sigma_s f_s\,. \tag{A2}$$

It is easily seen that if we rewrite the equations for the functions $f_s(\sigma_s)^{1/2}$ using the matching conditions for the functions f_s and $(d/dz)\sigma_s\, f_s$ at $|z|=w/2$, we obtain an equation for the eigenfunctions of a self-adjoint operator with the eigenvalues k^2. Consequently a full set of the solutions $f_{sn}(\sigma_s)^{1/2}$ of Eq. (A2) corresponding to the possible values of the parameters k_n^2 is a complete basis set for functions in the given interval $|z|<d/2$, $s=\pm 1$. Consequently, the general solution of Eq. (2) is given by

$$\mu_s=\sum_n (a_n e^{-k_n x}+b_n e^{k_n x})g_{sn}(z), \tag{A3}$$

where the constants a_n and b_n are determined by the boundary conditions at the ends of the spin guide. Using the orthogonality of the g_{sn} functions with different n yields

$$a_n=\frac{e^{k_nL}c_n-d_n}{e^{k_nL}-e^{-k_nL}},\quad b_n=\frac{d_n-e^{-k_nL}c_n}{e^{k_nL}-e^{-k_nL}},$$
$$c_n=\sum_s \int_0^{d/2}\mu_s(x=0,z)g_{sn}(z)dz, \tag{A4}$$
$$d_n=\sum_s \int_0^{d/2}\mu_s(x=L,z)g_{sn}(z)dz.$$

Here the origin of the coordinate system is located in the center of the entrance into the channel (see Fig. 1) and the orthonormal basis functions g_{sn} are given as

$$g_{sn}(z)=\sqrt{\sigma_s}f_{sn}(z)\left(\sum_s \int_0^{d/2}[\sqrt{\sigma_s}f_{sn}(z)]^2dz\right)^{-1/2}. \tag{A5}$$

The boundary conditions may be imposed in an alternative manner. Let the spin-up and spin-down current densities in the channel entrance be given by $J_s(z)$ and $\mu_s=0$ at the exit of the channel. Then it is easy to obtain the following expressions for the coefficients a_n and b_n:

$$a_n=\frac{c_n'}{1+e^{-2k_nL}},\quad b_n=-\frac{c_n'}{1+e^{2k_nL}},$$
$$c_n'=\frac{e}{k_n}\sum_s \int_0^{d/2}\sigma_s^{-1}J_s(x=0,z)g_{sn}(z)dz. \tag{A6}$$

Thus, according to Eq. (A3) we have to find the set of solutions of f_s for Eq. (A2) ($s=\uparrow$ or $\downarrow$); these solutions are related to the functions $f_\pm$ [see Eq. (4)] through Eq. (A1). Matching the functions $\mu_{\uparrow,\downarrow}$ and the currents (i.e., the derivatives $\sigma_{\uparrow,\downarrow}\partial\mu_{\uparrow,\downarrow}/\partial z$) at $z=\pm w/2$, we can find the relations between the coefficients A, B, C, and D, that is,

$$A\cos t_N+\frac{s}{2}C\cos t_N'=B\sin t_M+\frac{s}{2}\frac{\sigma_{M,-s}}{\sigma_{Mt}}D\sin t_M',$$
$$\sigma_N\left(Ak\sin t_N+\frac{s}{2}C\kappa_N\sin t_N'\right)$$
$$=\sigma_{Ms}\left(Bk\cos t_M+\frac{s}{2}\frac{\sigma_{M,-s}}{\sigma_{Mt}}D\kappa_M\cos t_M'\right), \tag{A7}$$
$$t_N=k\frac{w}{2},\quad t_N'=\kappa_N\frac{w}{2},\quad t_M=k\left(\frac{d-w}{2}\right),$$
$$t_M'=\kappa_M\left(\frac{d-w}{2}\right),\quad \sigma_{Mt}=\sigma_{M\uparrow}+\sigma_{M\downarrow}\,.$$

Here, the indices M and N denote the magnetic and nonmagnetic regions, respectively, and $\kappa_{N,M}$ are defined in Eq. (4). This set of equations can be simplified, and after some manipulations we obtain the following simple equations:

$$C\cos t_N'=D\sin t_M',\quad 2A\sigma_N\sin t_N=B\sigma_{Ms}\cos t_M\,. \tag{A8}$$

Elimination of B and D with the use Eqs. (A8) yields two equations for A and C. Equating the determinate of these equations to zero we obtain the equation that determines the possible values of the damping parameter k:

$$\left(1-\frac{2\sigma_N}{\sigma_{Mt}}\tan t_N\tan t_M\right)\left(\sigma_N\frac{\kappa_N}{\kappa_M}\tan t_N'\tan t_M'-2\frac{\sigma_{M\uparrow}\sigma_{M\downarrow}}{\sigma_{Mt}}\right)$$
$$=-\sigma_N\left(\frac{\sigma_{M\uparrow}-\sigma_{M\downarrow}}{\sigma_{Mt}}\right)^2\frac{k}{\kappa_M}\tan t_N\tan t_M'\,. \tag{A9}$$

For a given constant current density in the channel entrance ($J_{\uparrow,\downarrow}=J_0$ for $z<w/2$ and $J_{\uparrow,\downarrow}=0$ for $z>w/2$) and for $\mu_{\uparrow,\downarrow}=0$ at the channel exit, we obtain the following expressions for the spin-up and the spin-down currents in the channel:

$$I_s=2J_0\sum_n \frac{\cosh[k_n(L-x)]}{\cosh(k_nL)}\frac{\sigma_N}{K_n}\left(\langle f_+\rangle_c^2+\frac{s}{2}\langle f_+\rangle_c\langle f_-\rangle_c\right), \tag{A10}$$

where

$$K_n=\sum_s\int_0^{d/2}[\sqrt{\sigma_s}f_{sn}(z)]^2dz,\quad \langle\cdots\rangle_c\equiv\int_0^{w/2}\cdots dz.$$

Here k_n is determined by Eq. (A9). From the above we can calculate the degree of the spin polarization (α) of the current in the channel:

$$\alpha=\frac{I_\uparrow-I_\downarrow}{I_\uparrow+I_\downarrow}=\frac{\Sigma_n\frac{\cosh[k_n(L-x)]}{\cosh(k_nL)}\frac{\sigma_N}{K_n}\langle f_+\rangle_c\langle f_-\rangle_c}{2\Sigma_n\frac{\cosh[k_n(L-x)]}{\cosh(k_nL)}\frac{\sigma_N}{K_n}\langle f_+\rangle_c^2}. \tag{A11}$$

For the general case it is not possible to present the solution of Eq. (A3) analytically. However, one may obtain important analytical results if it is supposed that the spin guide is sufficiently long, i.e., when its length L is large enough compared to $k_{\min}^{-1}$ (where $k_{\min}$ is the smallest allowed value of k_n), i.e., $Lk_{\min}\gg 1$. Owing to this inequality and the vanishing boundary condition at the channel exit ($d_n=0$), the electrochemical potentials far from the entrance are given as [see Eqs. (A3) and (A4)]

$$\mu_s\cong c_{\min}(e^{-k_{\min}x}-e^{k_{\min}(x-L)})g_{s\,\min}(z)\quad\text{for}\quad x\gg k_{\min}^{-1}. \tag{A12}$$

The second term in parentheses is operative only at distances of the order of $k_{\min}^{-1}$ from the exit, and even there it does not change the order of magnitude of the current. Note that in this case the degree of spin polarization of the current in the channel, α, is determined by the functions $g_{s\,\min}$ [see Eq. (A12)]—this underlies the independence (to a good approximation) of α with respect to the x coordinate and the boundary conditions at the entrance. Using Eqs. (4) and (A3) it is easy to obtain the following expression for α, which is valid when Eq. (A12) is valid,

$$\alpha=\frac{\tan t_N'}{\tan t_N}\frac{k}{\kappa_N}\frac{\sigma_{Mt}-2\sigma_N\tan t_N\tan t_M}{\sigma_{M\downarrow}-\sigma_{M\uparrow}}. \tag{A13}$$

The relation between the coefficients C and A follows from Eq. (A7) and it has the form

$$C=2\alpha\frac{\sin t_N}{\sin t_N'}\frac{\kappa_N}{k}A, \tag{A14}$$

where α is determined by Eq. (A13). This equation together with Eqs. (A8) and (A9) allows us to find the potentials and the spin polarization of the current.

To calculate a concrete value of the current spin polarization one should find $k_{\min}$ from Eq. (A9), with the needed accuracy. In Sec. III we found asymptotically exact expressions for the degree of spin polarization of the current and for the damping parameter that are valid for different values of the physical parameters of our system.

Here we comment on the validity of the approximate expressions given in Eqs. (A12) and (A13). For distances along the channel axis that are larger than $k_{\min}^{-1}$ we use only one term of the sum (A3); this approximation demands that the difference between $k_{\min}$ and the next value of k_n is not too small compared with $k_{\min}$, since otherwise we should maintain two terms of the sum. As shown at the end of Sec. III B the latter is needed for a sufficiently high conductivity of the magnetic shell.

We did not attempt here a calculation of the preexponential factor $c_{\min}$ [see Eq. (A12)] for all possible configurations. This factor depends on the boundary conditions at the spin-guide entrance, which are determined by the details of the current injection process into the spin guide; this in turn requires information about the geometric characteristics of the current leads far from the spin guide. It appears to us that such a detailed picture is unwarranted for qualitative (and even semiquantitative) consideration. The coefficient $c_{\min}$ can be estimated as [see Eqs. (A4) and (A12)] $c_{\min}\approx U\sqrt{d}\approx(I/\sigma_N)k_{\min}\sqrt{d}$, where U is the potential difference along the spin guide and I is the current driven into the spin guide.

In addition to finding the solution of Eq. (A12), which is formed far from the entrance, we are interested in the way that the degree of spin polarization increases at distances that are shorter than $k_{\min}^{-1}$ in the case when spin-flip scattering events are rare. In order to obtain information about the latter issue we need to find additional solutions of Eqs. (A7) and (A9) that are related to the next value of k_n (i.e., the one after $k_{\min}$). If we neglect the first term in the right-hand side of Eq. (A2) (in the approximation of absence of spin-flip processes), Eqs. (A7) reduces to a couple of two independent equations for the spin-up and spin-down components. Hence, we can write two types of solutions of these equations as given in Eqs. (5a) and (5b) (inside of the nonmagnetic channel, and in the magnetic shell), and the corresponding damping parameters ($k_{\uparrow,\downarrow}$) are given as solutions of Eq. (6). Consequently, the spin-down current, which penetrates preferentially (in comparison to the spin-up component) into the magnetic material, decays over a distance $k_{\downarrow\min}^{-1}$. If one allows spin-flip scattering, $k_{\uparrow\min}$ can be replaced by $k_{\min}=k_0$, which is the smallest allowed value of the parameter k in Eq. (A9), and $k_{\downarrow\min}$ can be replaced by k_1. Equation (5) is valid for distances $k_{\downarrow\min}^{-1}<x<k_{\uparrow\min}^{-1}$ from the entrance, and we can rewrite it through the normalized functions $g_{\uparrow,\downarrow}(z)$ and the corresponding coefficients $a_{\uparrow,\downarrow}$ [see Eq. (A3)]

$$\mu_{\uparrow,\downarrow}=a_{\uparrow,\downarrow}\exp(-k_{\uparrow,\downarrow}x)g_{\uparrow,\downarrow}(z). \tag{A15}$$

The constants $a_{\uparrow,\downarrow}$ in this equation are determined by the boundary conditions. Spin-flip processes are assumed to be rare and we obtain $a_\uparrow\cong a_0$ and $a_\downarrow\cong a_1$ [see Eqs. (A3) and (A4)]. In the approximate expressions for the degree of spin polarization of the current [Eqs. (7) and (11) in the text] the spin polarization is determined up to the corresponding preexponential factors ($a \propto a_{\uparrow}/a_{\downarrow}$); as discussed following Eq. (7) these preexponential factors are close to unity in the case when the magnitudes of the spin-up and spin-down currents are close to each other at the entrance of the spin-guide.

Figure 2, which shows the results of numerical calculations of the spin-up and spin-down currents in the channel [Eq. (A10)], together with Fig. 3, illustrates the domain of applicability of Eqs. (5a), (5b), and (A12). As may be concluded from inspection of Fig. 2, the current calculated with the damping parameters $k_{\uparrow,\downarrow}$ coincides with the exact solutions already at $x > d/2$. Equation (A12) is valid (and, correspondingly, the current spin polarization is saturated) as demonstrated in Fig. 3 for distances x that are much larger than $d/2$.

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