Spin current diode based on an electron waveguide with spin-orbit interaction

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We propose a spin current diode which can work even in a small applied bias condition (the linear-response regime). The prototypical device consists of a hornlike electron waveguide with Rashba spin-orbit interaction, which is connected to two leads with different widths. It is demonstrated that when electrons are incident from the narrow lead, the generated spin conductance fluctuates around a constant value in a wide range of incident energy. When the transport direction is reversed, the spin conductance is suppressed strongly. Such a remarkable difference arises from spin-flipped transitions caused by the spin-orbit interaction.

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The spin of carriers has been exploited in recent years to develop solid-state devices combining the standard microelectronics with spin-dependent effects. The operation of spin-based electronic circuits requires the electrical generation of excess spin in nonmagnetic materials. To this end, various spin injection methods and spin filters have been explored. For a spin filtering device it would be very desirable that the spin polarization (both amplitude and orientation) of the outgoing current could be controllable by electric means. As an example, the concept of spin filtering diode has been put forward based on the giant Zeeman splitting in semimagnetic semiconductor heterostructures. Its salient feature lies in the large difference of spin polarization when switching the polarity of the dc bias applied to the device. The rectification of spin current has also been predicted in asymmetric systems composed of either a molecular wire or a quantum dot sandwiched by a ferromagnetic and a nonmagnetic lead. In these systems the ferromagnetic lead is essential to generate a spin-polarized current.

The presence of spin-orbit interaction (SOI) in semiconductors provides a way to design spintronic devices without need for a magnetic element or an external magnetic field. Several devices utilizing multiterminal electron waveguides have been proposed to generate spin-polarized currents by means of the SOI alone. For a two-terminal stub waveguide structure, we have shown that the SOI-induced effective magnetic field can generate both spin localization inside the stub and spin polarization in the transmitted electron beam near structure-induced Fano resonances. We have also shown that the SOI alone can not generate a spin-polarized transmitted electron beam in a two-terminal waveguide when the output lead supports only one orbital channel. Inspired by this fact, we will show, in this work, that the spin transport properties of a hornlike waveguide can be utilized to devise a spin current diode without need for a ferromagnetic material or a magnetic field.

Our system is illustrated in the inset of Fig. 1(c), where a two-dimensional electron gas (2DEG) in the \((x, y)\) plane is restricted to a waveguide along the \(x\) direction by a hard-wall confinement potential \(V_c(x, y)\). The 2DEG is contained in an asymmetric quantum well so that the SOI arises mainly from the interfacial electric field (the Rashba mechanism). The waveguide consists of three parts. The left (right) part has a length \(L_1 (L_3)\) and a uniform width \(W_L (W_R)\), connected to the left (right) lead with the same width. A finite difference between the widths of the left and right parts of the waveguide \((W_L, W_R)\) is essential for the proposed device. Since we are concerned only with spin-unpolarized injection, the two connecting leads are nonmagnetic and have a vanishing SOI. The central part of the waveguide spans the region \((x_0, x_0 + L_2)\) along the \(x\) direction, within which the waveguide width \(W_C\) varies smoothly from the initial value \(W_L\) to the final value \(W_R\). To be specific, we take

\[
W_C(x) = W_L + (W_R - W_L) \sin^2 [\pi (x - x_0)/(2L_2)].
\]

For simplicity we assume that the whole waveguide shares a common horizontal central line \((y = 0)\). The effective-mass Hamiltonian describing the considered system reads

\[
H = \left[ \frac{1}{2m^*} \left( p_x^2 + p_y^2 \right) + V_c(x, y) \right] \sigma_0 + \frac{1}{2\hbar} \left[ \alpha(x, y) (\sigma_x p_y - \sigma_y p_x) + \text{H.c.} \right].
\]

Here \(m^*\) is the effective mass of electrons, \(p_x\) and \(p_y\) are the in-plane momentum components, \(\sigma_x, \sigma_y,\) and \(\sigma_z\) are the three Pauli matrices, and \(\sigma_0\) is the \(2 \times 2\) unit matrix. The Rashba SOI strength \(\alpha(x, y)\) is assumed to be uniform (with a value \(\alpha\) in the central part of the waveguide and decreases adiabatically down to zero in the transition regions of the entrance and exit. We take the spin quantum axis to be along the transverse \(y\) direction, so that \(|\uparrow\rangle = (1, i)^T / \sqrt{2}\) and \(|\downarrow\rangle = (1, -i)^T / \sqrt{2}\) represent the spin-up and spin-down states, respectively.
A real-space discretization of Eq. (2) yields a tight-binding model, which can be solved numerically by means of the recursive Green’s function method to obtain the outgoing wave amplitudes. The Landauer–Büttiker formula is then used to determine the spin-resolved conductances \(G_{\sigma,\sigma}(\sigma',\alpha = \pm 1)\), which depend both on the incident spin states \(|\sigma\rangle\) in one lead and on the outgoing spin states \(|\sigma'\rangle\) in the other lead.

The transmitted spin current in the linear-response regime is characterized by the spin conductance \(G_{s,x}, G_{s,y}, G_{s,z}\) \(^\text{(4)}\) Since our system is invariant under the operation \(R_y\sigma_y\), where \(R_y\) is the reflection \(y \rightarrow -y\), the spin conductance could be nonvanishing only along the \(y\) direction and is given by

\[
G_{s,y} = \frac{-e}{4\pi} \frac{G_{1,\uparrow} + G_{1,\downarrow} - G_{1,\downarrow} - G_{1,\uparrow}}{c^2/\hbar}.
\]  

(3)

In the calculations we have chosen to fix the size parameters \(W_L = W_R/2 = 100\ nm\) and \(L_1 = L_2 = L_3 = 100\ nm\). The electron effective mass has been taken to be \(0.041\ m_0\) \((m_0\ is\ the\ free-electron\ mass)\), which is appropriate to an InGaAs quantum well system. \(^\text{(2)}\)

In Fig. 1 we plot the total charge conductance \(G = G_{1,\uparrow} + G_{1,\downarrow} + G_{1,\uparrow} + G_{1,\downarrow}\) and the normalized spin conductance \(G_{s,y}\) \([\text{in\ unit\ of}\ -e/(4\pi)]\) as functions of the Fermi wave vector \(k_F = (2m^*E_F/\hbar^2)^{1/2}\), where \(E_F\) is the electron Fermi energy, for several values of the SOI strength \(\alpha\). Here \(k_F\) is given in units of \(k_1 = \pi/W_L\), a value corresponding to the first subband energy \(E_1\) in the narrow lead. The charge conductance exhibits a steplike feature \([\text{see\ Fig.}\ 1(\text{a})]\) and is determined by the number of propagating modes in the narrow lead, \(N_c(E_F)\).

This indicates a negligible backscattering when electrons traverse the considered waveguide structure from the narrow lead to the wide lead (the forward transport direction), that is

\[
G_{1,\downarrow}^{L,R} + G_{1,\uparrow}^{L,R} \approx N_c(E_F)e^2/\hbar \approx G_{1,\uparrow}^{L,R} + G_{1,\downarrow}^{L,R}. \]  

(4)

The left-to-right and right-to-left charge conductances, \(G_{L,R}\) and \(G_{R,L}\), are identical due to the time reversal symmetry. In contrast, the spin conductance changes remarkably once the transport direction is reversed. Under the forward bias, the spin conductance fluctuates around a single plateau to the wide lead (the transport direction). The plateau moves up as the SOI strength increases. The derivation of \(G_{s,y}^{L,R}\) from the plateau value occurs in the energy region \(E_1 < E_F < 4E_1\) and near the onset of subbands in the narrow lead. The spin polarization of the current is the ratio between the normalized spin conductance and the normalized charge conductance. \(^\text{(5)}\) As a result, the spin polarization exhibits a steplike decrease as the Fermi energy increases.

When electrons are incident from the wide lead, the spin conductance and thus the spin polarization is greatly suppressed \([\text{see\ Fig.}\ 1(\text{c})]\). A vanishing spin current is found in the energy region \(E_F < 4E_1\), in which the outgoing lead (the left lead in this case) can support the lowest orbital mode only. This is in full agreement with the prediction of Ref. \(^\text{(15)}\). When the outgoing lead supports two or more propagating orbital modes, the spin conductance can be finite but it is rather small in general \([\text{Fig.}\ 1(\text{c})]\). A narrow peak is observed near the onset of a subband (with subband index \(>1\)) of the outgoing lead, which is due to SOI-induced Fano resonance. \(^\text{(6)}\)

The contrast in the spin conductance between the forward and backward transport directions indicates a spin current diode even in the small bias condition (the linear-response regime). The spin current of the "on" state (the forward biased case) can be controlled by the SOI strength. For the "off" state (the backward biased case), the spin current is weak when the charge conductance is on a quantized plateau or vanishing when the Fermi energy is in the region of \([E_1, 4E_1]\). The results can be understood as follows. The spin conductance comes from two parts \(G_{s,y} = G_{s,1} + G_{s,2}\). One is the difference between the two spin-conserved conductances \(G_{s,1} \propto G_{1,\downarrow} - G_{1,\uparrow}\) and the other one is the difference between the two spin-flipped conductances \(G_{s,2} \propto G_{1,\uparrow} - G_{1,\downarrow}\). We first consider the situation that electrons are incident from the left (narrow) lead. From Eq. \(^\text{(4)}\) we know that the two parts, \(G_{s,1}\) and \(G_{s,2}\), are almost identical. Thus, the spin conductance \(G_{s,y}^{L,R}\) can be expressed in terms of the difference between the two spin-flipped conductances,

\[
G_{s,y}^{L,R} \approx -e/(2\pi)(G_{1,\downarrow}^{L,R} - G_{1,\uparrow}^{L,R})/(e^2/\hbar). \]  

(5)

Such a difference is reflected by the variations of spin-flipped transmissions \(T_{q\sigma \rightarrow \sigma'}\) as shown in Fig. 2. Here, \(\bar{\sigma} = -\sigma\), while \(p\) and \(q\) are the indices of the incident and outgoing modes, respectively. The \(\bar{R}_y\sigma_y\) symmetry of the considered system implies

\[
T_{q\sigma \rightarrow \sigma'} = 0, \ p - q \equiv 0 \ mod 2. \]  

(6)

It can be seen that each nonvanishing transmission \(T_{q\sigma \rightarrow \sigma'}\) is remarkable only within an energy window. When the left lead supports only a single orbital channel \([\text{Figs.}\ 2(\text{a})\ and\ (\text{b})]\), the spin-flipped transmission for the spin-down injection is much larger than that for the spin-up injection. This can be explained by examining the SOI-induced mode mixing between subbands of different spins in the central part of the considered waveguide. \(^\text{(19)}\) As two or more orbital modes are allowable for conducting in the left lead \((p > 1)\), \(T_{q\sigma \rightarrow \sigma'}^{L,R}\) can be remarkable and even exceed the corresponding \(T_{q\sigma \rightarrow \sigma'}^{L,R}\) in certain energy windows \([\text{see}\ Figs.\ 2(\text{c})-2(\text{f})]\). However, the spin-flipped transmissions \(T_{q\sigma \rightarrow \sigma'}^{L,R}\) for spin-down injections are seen to be in general larger than their corresponding spin-flipped transmissions \(T_{q\sigma \rightarrow \sigma'}^{L,R}\) over large energy regions. Furthermore, there exists such an outgoing channel \(q = p'\) that \(T_{q\sigma \rightarrow \sigma'}^{L,R}\) is much smaller than \(T_{q\sigma \rightarrow \sigma'}^{L,R}\). The combination of these facts gives rise to a nearly constant spin conductance.

When the transport direction is reversed, the spin-resolved conductance can be obtained from the relation imposed by the time reversal symmetry,

\[
G_{\sigma,\sigma}^{R,L} = G_{\sigma,\sigma}^{L,R}, \ G_{\sigma,\sigma}^{R,L} = G_{\sigma,\sigma}^{L,R}. \]  

(7)

This relation together with Eq. \(^\text{(4)}\) indicates a cancellation of \(G_{s,1}\) and \(G_{s,2}\) and thus results in \(G_{s,y}^{R,L} \approx 0\), as observed in Fig. 1(c). From the above analysis one can see that the spin current diode proposed here relies only on two gradients: the quantized conductance and the difference of the two spin-flipped conductances. Equation \(^\text{(7)}\) also indicates that for a spin-conserved system, such as the system studied in Ref. \(^\text{(3)}\).
the diode function of spin current can be performed only in the nonlinear-response regime.

In conclusion, we have proposed a spin current diode based on a waveguide connected to two leads with different width. It is demonstrated that the spin conductance fluctuates around a constant value in a wide range of incident energy when electrons are incident from the narrow lead. When the transport direction is reversed, the spin conductance is suppressed strongly. The rectification of spin current is achievable even in the linear-response regime and thus the proposed diode can work at a low power consumption condition. The SOI alone is utilized to realize such a function of spin current rectification.

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FIG. 1: (Color online) Conductance spectra of a two-terminal horn-like waveguide structure with the Rashba SOI plotted as functions of the Fermi wave vector for spin-unpolarized electron injections: (a) total conductance $G$ (in unit of $e^2/h$); (b) and (c) spin conductances $G_{L\rightarrow R}^{a}$ and $G_{R\rightarrow L}^{a}$ [both in unit of $-e/(4\pi)$] for the forward and backward transport directions, respectively. The inset in panel (c) illustrates schematically the considered waveguide structure. The structural parameters are given in the text.
FIG. 2: (Color online) Typical spin-flipped transmission probabilities $T_{q\bar{\sigma}\rightarrow p\sigma}^L$ for electrons with spin $\sigma$ incident from the subband $p$ in the narrow lead scattering into the subband $q$ in the right lead with opposite spin. The structural parameters are the same as those in Fig. 1 and the Rashba SOI strength is set at $\alpha = 25$ meV nm. Note that for the considered structure depicted in the inset of Fig. 1(c), $T_{q\bar{\sigma}\rightarrow p\sigma}^L$ vanishes when modes $p$ and $q$ have the same parity.