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A spin polarized device constructed with spin–orbit coupled semiconductors

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Abstract
On the basis of the Rashba spin–orbit interaction, we propose and investigate a mesoscopic spin interferometer for generating spin polarized current. We find that the output current is in general spin polarized if the interferometer is a multi-terminal device with two non-equal-length arms. We study the dependence of the spin polarization and output probability on the system parameters, and find that both of them can be quite large, simultaneously. The suggested device does not contain any magnetic material or magnetic field; moreover, the spin–orbit interaction can be either uniform or non-uniform. This spin device can be realized with today's technology.

How to build a controllable source with a spin polarized current in a semiconductor has been one of the most important issues in condensed matter physics [1–4]. Many approaches have been proposed in the past two decades; however none is very satisfactory. A natural idea is to inject the spin polarized electrons into a semiconductor from a polarized source, e.g. a ferromagnet [1, 4–6]. However, due to the mismatch of the conductivities between the ferromagnetic metals and the semiconductors, the spin-injection rate is usually very low, e.g. lower than a few per cent [6, 7]. Recently, on the basis of the spin–orbit (SO) interaction, some theoretical works have put forward a different route for generating a spin polarized current without the ferromagnetic materials [8–14]. For example, Voskoboynikov *et al* and Koga *et al* point out that double-barrier and triple-barrier multi-layer resonant tunnelling structures having a SO interaction in the middle-well layer can work as spin filters [8, 9]. Ionicioiu and D'Amico designed a spin polarized device consisting of a mesoscopic Mach–Zehnder interferometer with a Rashba SO interaction existing only in one arm and a threading AB magnetic flux [10]. Sun and Xie proposed a device having a spontaneous spin polarized current with a non-uniform multi-terminal Rashba SO interaction system [12]. The SO interaction is an intrinsic property, originating from a relativistic effect. In a SO interaction system, a new effect, the spin Hall effect, was theoretically predicted and has been extensively studied recently [15]; it can generate the spin current in a direction perpendicular to the bias voltage direction [16].

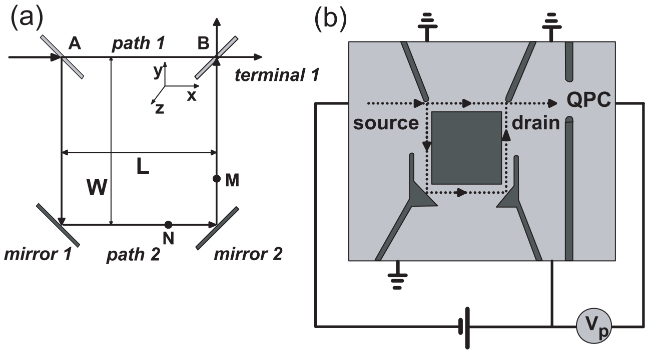

Figure 1. (a) Schematic diagram for the spin interferometer which consists of two mirrors and two beam splitters (A and B). (b) Schematic diagram for the suggested experimental device fabricated in a 2DEG. In the dark region electrons are depleted by the nanofabrication process. Here the interferometer is for generating the spin polarized current and the QPC is for measuring this current.

In this paper, by using the Rashba SO interaction we present an apparatus for generating spin polarized current with substantial polarization and output current simultaneously. This apparatus has the following advantages: (1) no ferromagnetic material or magnetic field is present; (2) the SO interaction can be either uniform or non-uniform; note that although some recent works mentioned above have proposed a couple a schemes for generating a spin polarized current by SO interaction, they all require a non-uniform Rashba SO interaction [10, 12, 13]; (3) spin polarized current is generated in the biased voltage direction; typically the current along the bias direction is much larger than the current perpendicular to it; (4) the proposed apparatus can not only work in the ballistic regime but also in the diffusive regime.

The proposed scheme is displayed in figure 1(a) which consists of a spin Mach–Zehnder interferometer having two mirrors and two beam splitters (BS) fabricated in a Rashba SO coupled two-dimensional electron gas (2DEG) [17–19]. We assume that the size of the device, i.e. the length L and the width W, are within the phase coherent length range. Also we first assume electrons travel ballistically through the interferometer. In fact, the ballistic travel assumption can be relaxed, and the device will still work in the diffusive regime (see the discussion below).

An incident electron can be described by

$$\phi = \begin{pmatrix} \cos(\frac{\alpha}{2})e^{i\beta/2} \\ \sin(\frac{\alpha}{2})e^{-i\beta/2} \end{pmatrix} = \begin{pmatrix} \xi \\ \chi \end{pmatrix}, \tag{1}$$

where α and β are the spin Euler angles. The incident electron ϕ first hits BS A, and it is split into two identical beams [19], with the transmitted wave $\frac{\sqrt{2}}{2}\phi$ and the reflected wave $\frac{\sqrt{2}}{2}\phi e^{i\pi/2}$, in which the reflected wave has acquired an extra phase of $\pi/2$ [10]. Afterwards, the transmitted wave propagates directly to BS B following path 1 in figure 1(a). But the reflected wave follows path 2, in which it passes mirror 1 and mirror 2, and finally also reaches BS B. In BS B, the two waves meet and interference occurs. In the following, we study the output current at terminal 1.

With the Rashba SO interaction in the device [20, 21], the electron spin undergoes precession when the electron propagates [22]. Correspondingly, the wavefunction changes into $R_{\hat{r}}(\theta)\phi$ with the rotation operator $R_{\hat{r}}$ as [19]

$$R_{\hat{r}}(\theta) = \mathbf{I}\cos(\theta/2) - i\hat{r}\cdot\boldsymbol{\sigma}\sin(\theta/2), \tag{2}$$

where $\mathbf{I}$ is the identity matrix and $\boldsymbol{\sigma}$ are Pauli matrices. The direction $\hat{r} = \hat{z} \times \hat{D}$ is in the plane of the 2DEGs and is perpendicular to the electron propagation direction $\hat{D}$, and $\theta = -m^\star \alpha_R D/\hbar^2$ represents the precession angle with the propagation distance D, $m^\star$ is the electron effective mass, and α_R is the Rashba coefficient [19, 22]. For example, the rotation operator for an electron from BS A propagating to BS B is $R_{\hat{y}}(\theta_L)$ with $\theta_L = -m^\star \alpha_R L/\hbar^2$, and that for one from BS A travelling to mirror 1 is $R_{\hat{x}}(\theta_W)$ with $\theta_W = -m^\star \alpha_R W/\hbar^2$. In the following we assume the Rashba coefficient α_R to be uniform throughout the interferometer. But this assumption can certainly be relaxed. Also note that the lengths of path 1 and path 2 are not equal. As a result, a phase difference $\gamma = 2$ kW is acquired for an electron following these two paths, where k is the wavevector of the incident electron.

Combining all the above-mentioned factors, the output wavefunction at terminal 1 is obtained as

$$\phi_{out} = \tfrac{1}{2} e^{ikL} [R_{\hat{y}}(\theta_L) + e^{i\gamma} R_{-\hat{x}}(\theta_W) R_{\hat{y}}(\theta_L) R_{\hat{x}}(\theta_W)]\phi. \tag{3}$$

The output wavefunction ϕ_{out} can be expressed as $\phi_{out} = \mathcal{R}\phi$, with $\mathcal{R} = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$ being a 2×2 complex matrix. In the following we consider that the incident electron is spin unpolarized. So in order to obtain a physical quantity A, we need to calculate the expectation value by averaging over the Euler angles of the spin direction of the incident electron: [19] $\int_0^\pi d\alpha\, \sin\alpha \int_0^{2\pi} d\beta\, \langle \phi_{out}|\hat{A}|\phi_{out}\rangle \equiv \langle\langle \phi_{out}|\hat{A}|\phi_{out}\rangle\rangle$. Thus the output probability O and the spin polarization P in the z direction are

$$O = \langle\langle \phi_{out}|\phi_{out}\rangle\rangle = \tfrac{1}{2}(|a|^2 + |b|^2 + |c|^2 + |d|^2), \tag{4}$$

$$P = \langle\langle \phi_{out}|\sigma_z|\phi_{out}\rangle\rangle = \frac{|a|^2 + |b|^2 - |c|^2 - |d|^2}{|a|^2 + |b|^2 + |c|^2 + |d|^2}. \tag{5}$$

Before presenting our numerical results, we mention two general properties: (i) for a two-terminal system, one can prove that the output current is spin unpolarized due to the time-reversal invariance and the current conservation [12]; (ii) if the lengths of the two paths are equal, there is no spin polarized output current. However, the present device is a multi-terminal system with two non-equal propagation paths, so in general it produces spin polarized current.

Let us estimate the device parameters. The wavevector k of the incident electron is near the Fermi wavevector $k_F = \frac{2\pi}{\lambda_F} = \sqrt{2\pi n_0}$, with n_0 being the electron density. n_0 is typically in the range from 2×10^{11} to 2×10^{12} cm^{-2} [23]. If we take $n_0 = 3.0 \times 10^{11}$ cm^{-2}, $\lambda_F \approx 45.7$ nm. So we take the Fermi wavelength $\lambda_F = 45$ nm in our numerical calculations. The Rashba coefficient α_R is around 3×10^{-11} eV m [24]. Thus, the spin precession angle $\theta_0 = -m^\star \alpha_R L_0/\hbar^2$ may reach $\pi/2$ for a length $L_0 = 100$ nm and $m^\star = 0.036 m_e$.

Next, we present our numerical results. Figure 2 shows the spin polarization P versus the spin precession angle θ_0 and the size L in a square device with $L = W$. Here $\theta_0 \equiv -m^\star \alpha_R L_0/\hbar^2$ is the spin precession angle at a fixed length $L_0 = 100$ nm and $m^\star = 0.036 m_e$. So varying θ_0 is equivalent to varying the Rashba coefficient α_R. The spin polarization P is a quasi-periodic function of both θ_0 and L, and figure 2 shows a typical cell. It exhibits that the output current is indeed spin polarized. With a large range of θ_0 and L, the polarization $|P|$ maintains large values, e.g. over 0.4. In some special positions, P can reach ± 1. When 90.0 nm $\leqslant L \leqslant$ 101.25 nm, P is negative, but for 101.25 nm $\leqslant L \leqslant$ 112.5 nm, P is positive. For application purposes, besides a large polarization P, it also desirable to have a large output probability O. In the present device, O is also quite large, e.g. $O > 0.1$ in most places, except for the four corners and the centre region in figure 2. Near the symmetric centre region, O is very small, so P can be easily changed between ± 1.

In order to clearly show the relation of P and O with θ_0, the detailed data in figure 2 for $L = 98$, 100, 103, and 105 nm are plotted in figure 3. When $\theta_0 = 0$ (i.e. without Rashba SO

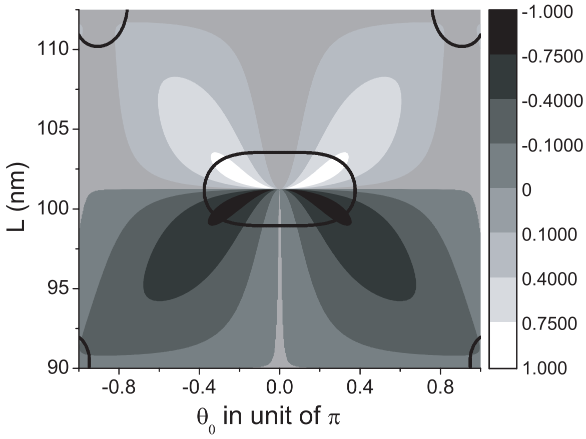

Figure 2. Spin polarization P versus θ_0 and the size L for the square device ($L = W$) at $\lambda = \lambda_F = 45$ nm. The thick solid curves are the boundaries for the output probabilities $O > 0.1$ and $O < 0.1$.

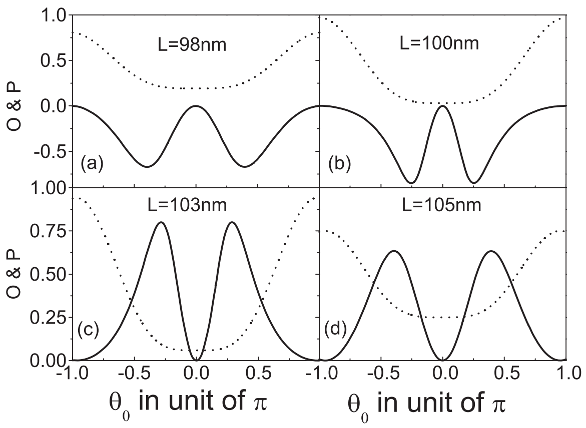

Figure 3. Spin polarization P (solid curves) and output probability O (dotted curves) versus θ_0 for the square device ($L = W$) at $\lambda = \lambda_F = 45$ nm with different sizes L.

interaction), $P = 0$ and the output current is unpolarized. With increasing $|\theta_0|$, $|P|$ quickly rises. At $|\theta_0| = 0.2\pi$, $|P|$ is over 0.3 for all L values. Curves for $L = 100$ nm (in figure 3(b)) and 103 nm (in figure 3(c)) are near the symmetric centre (see figure 2), at which P and O cannot be large at the same time. On the other hand, the curves for $L = 98$ nm (in figure 3(a)) and 105 nm (in figure 3(d)) are slightly away from the symmetric centre, where both the spin polarization P and the output probability O are substantial. For example, for $L = 105$ nm, $O > 0.25$ and $P > 0.3$ when $0.2\pi < |\theta_0| < 0.6\pi$.

If the device fabricated deviates from a square shape, i.e. $L \neq W$, how are the polarization P and the output probability O effected? Figure 4 shows P and O versus W with a fixed $L = 105$ nm. Both P and O exhibit oscillatory behaviour and they have large values at $L \neq W$. When $W = 0$, the two travelling paths for the electron are of the same length, so the polarization P is exactly zero which is consistent with the above-mentioned general property. With varying W/L, P may change its sign. For a small θ_0 (e.g. $\theta_0 = 0.2\pi$, see figure 4(a)), P

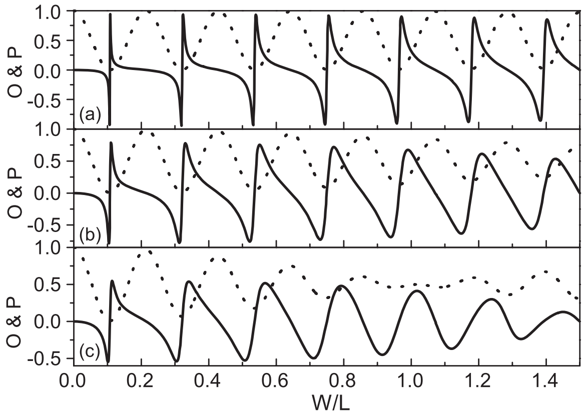

Figure 4. Spin polarization P (solid curves) and output probability O (dotted curves) versus W/L at $\lambda = \lambda_F = 45$ nm and $L = 105$ nm. The parameter θ_0 is 0.2π (a), 0.4π (b) and 0.6π (c).

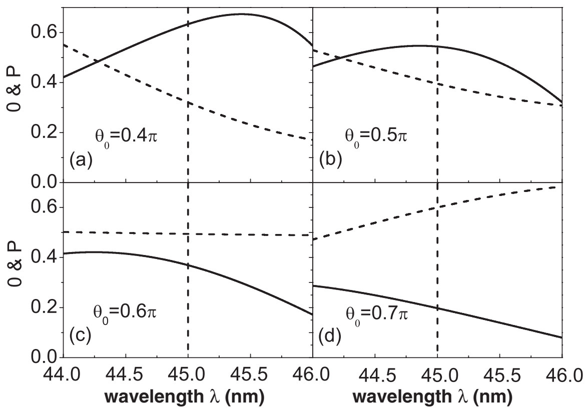

Figure 5. Spin polarization P (solid curves) and output probability O (dotted curves) versus λ for the square device with $L = W = 105$ nm for different values of θ_0.

changes abruptly from -1 to 1 in places with low output probability O. But for slightly larger θ_0 (e.g. $\theta_0 = 0.4\pi$ or 0.6π in figures 4(b) and (c)), P and O vibrate smoothly with W/L. In particular, in the case of $\theta_0 = 0.6\pi$, both P and O can be quite large simultaneously over an extensive range of W/L from $W/L = 0.4$ to 1.5 (see figure 4(c)).

In the above investigation, we take $\lambda = \lambda_F$ (i.e. $k = k_F$). However if, in the case of a finite bias or non-zero temperature, the wavelength λ of an incident electron has a distribution around λ_F, then the spin polarization P and output current O must average over the λ distribution. Will they still be large enough after the averaging? Figure 5 displays P and O versus the wavelength λ for different values of θ_0. Here the changes of P and O are smooth, and they have large values over a rather wide range of λ. Therefore it is possible that both P and O maintain large values after the averaging. Note that in figure 5 the change of the wavelength λ from 44 to 46 nm is rather large; it corresponds to an energy difference of $\Delta E = 2$ meV. In other words, if the bias went up to 2 mV or the temperature up to 20 K, the above results were almost unaffected.

Up to now, we have only considered a ballistic device. But in an experiment, impurity scattering and backscattering by the mirrors are always present to a certain degree. If there exists some scattering, or if the device is in the diffusive regime, can the proposed apparatus still work? Intuitively, from the oscillatory behaviour of the spin polarization P versus the length $(2W + L)$ of path 2 (see figure 4), the polarization P seems to be destroyed by the scattering which effectively increases the travelling length. However, we emphasize that this intuitive picture is incorrect and the polarization $|P|$ is almost unaffected by the scattering. In other words, the proposed apparatus can still work in the diffusive regime [25][3,4].

Let us consider there to exist some scatterers in the lower arm (i.e. path 2 in figure 1(a)). Due to the scattering, the electron travelling through this arm follows many paths. In order to have a clear understanding, let us first consider two paths: one path is without scattering, from BS A through mirrors 1 and 2 to BS B, and its output wavefunction is $\frac{1}{2}e^{ikL}e^{i\gamma}t_1 R_{-\hat{x}}(\theta_W)R_{\hat{y}}(\theta_L)R_{\hat{x}}(\theta_W)\phi$, where $\gamma = 2kW$ and t_1 is real. The other path contains the scattering, e.g. the electron is scattered back at the point M and then it goes ahead again by scattering at the point N (see figure 1(a)). In this path, although the electron travelling length is obviously increased, the spin precession factor $R_{-\hat{x}}(\theta_W)R_{\hat{y}}(\theta_L)R_{\hat{x}}(\theta_W)$ is not affected at all. Because when the electron is scattered back, the spin also correspondingly precesses back, the total precession factor is invariant [25] (see footnotes 3 and 4). We emphasize that this contrasts with the varying W in figure 4, for which the precession factor is dependent on the travelling length $2W + L$. Then the output wavefunction in the scattering path is $\frac{1}{2}e^{ikL}e^{i\gamma}t_2 R_{-\hat{x}}(\theta_W)R_{\hat{y}}(\theta_L)R_{\hat{x}}(\theta_W)\phi$, where $\frac{1}{2}e^{ikL}e^{i\gamma}t_2$ is the transmission coefficient without the Rashba SO interaction. Therefore the total output wavefunction at terminal 1 is

$$\phi_{\mathrm{out}} = \tfrac{1}{2}e^{ikL}[R_{\hat{y}}(\theta_L) + e^{i\gamma}(t_1 + t_2)R_{-\hat{x}}(\theta_W)R_{\hat{y}}(\theta_L)R_{\hat{x}}(\theta_W)]\phi. \tag{6}$$

This equation is similar to equation (3), and the output current is evidently spin polarized.

Next consider there to exist many paths in the lower arm due to the scattering, and note that the spin precession factor is the same for all paths [25] (see footnotes 3 and 4); then the total output wavefunction at terminal 1 can be obtained straightforwardly:

$$\phi_{\mathrm{out}} = \tfrac{1}{2}e^{ikL}\left[R_{\hat{y}}(\theta_L) + e^{i\gamma}\left(\sum_j t_j\right)R_{-\hat{x}}(\theta_W)R_{\hat{y}}(\theta_L)R_{\hat{x}}(\theta_W)\right]\phi. \tag{7}$$

where $e^{ikL}e^{i\gamma}t_j$ is the coefficient of transmission through path j at $\alpha_R = 0$, and $e^{ikL}e^{i\gamma}\sum_j t_j \equiv t_{\mathrm{lower}}$ is the total coefficient of transmission through the lower arm. Assuming the probability distribution of the electron travelling length to be proportional to $e^{-x/D}$, where $x + 2W + L$ $(x \geqslant 0)$ is the electron travelling length, and D describes the average distance of the electron travelling length, and thus D also represents the scattering strength, then $\sum_j t_j = c\int_0^\infty e^{ikx}e^{-x/D}\,dx$, where c is a constant coefficient. For $D = 0$, an electron travels ballistically without any scattering. Figure 6 shows the spin polarization P versus D at $|t_{\mathrm{lower}}| = 1$ for different values of W/L.[5] This exhibits that with increasing D, $|P|$ can be reduced for some W/L, but $|P|$ can also be enhanced for other W/L. In fact, the action of the scattering only effects a translation on the curve P–W/L in figure 4, and the polarization P is almost

[3] Here we have assumed that the arm of the spin Mach–Zehnder interferometer is one dimensional. If the arm is wide, the D'yakonov–Perel' spin relaxation occurs and the total precession factor is changed; then the spin polarization P is severely reduced. However, if the width W_a of the arm is less than 20 nm, the separation of the subband is $(2^2 - 1^2)\hbar^2\pi^2/2m^\star W_a^2 \approx 125$ meV, which is quite large. Then the device is well represented by a one-dimensional system, and the scattering will not strongly affect the polarization $|P|$. For example, see also D'yakonov and Perel' or Bournel *et al* [25].

[4] Notice that here we only consider elastic scattering. If inelastic scattering occurs, the momentum as well as the energy of the electron is varied in the scattering, and the phase coherence is lost. Then the polarization P will be strongly reduced. So we require the size of the proposed device to be within the phase coherence length region.

[5] With the existence of scattering, the transmission probability $|t_{\mathrm{lower/upper}}|^2$ of the lower/upper arm can be less than 1. In this case, the spin polarization $|P|$ can still be large, except for $|t_{\mathrm{lower}}|/|t_{\mathrm{upper}}| \ll 1$ and $|t_{\mathrm{lower}}|/|t_{\mathrm{upper}}| \gg 1$.

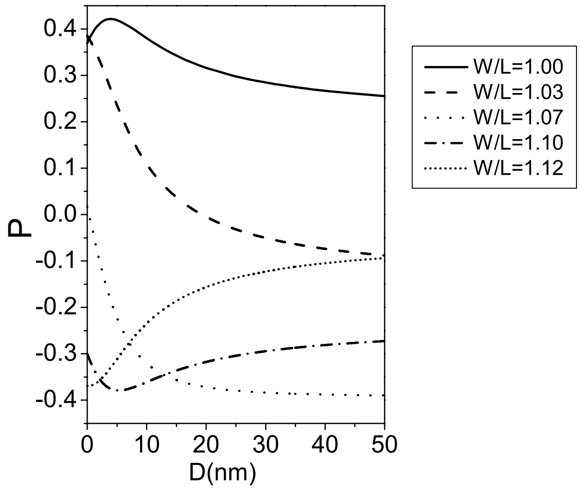

Figure 6. Spin polarization P versus the scattering strength D for different values of W/L. The other parameters are the same as for figure 4(c).

unaffected (see footnote 5). The key point as regards why P is not affected by scattering comes from the fact that the spin precession factor is independent of the scattering. In fact, this is similar to the AB (Aharonov–Bohm) effect; there the extra phase from the magnetic flux is also independent of the scattering. So the spin polarized current in the present device, similarly to the AB effect, can survive in the diffusive regime.

In the above discussions, we only consider the Rashba SO interaction in the device. Recent experiments have demonstrated that the Dresselhaus SO interaction may also exist, e.g. in InAs quantum wells reported by Ganichev *et al* [26]. We emphasize that if the arm of the spin interferometer is one dimensional (i.e. only one subband is active [25] (see footnote 3)), the proposed apparatus can still work and the polarization $|P|$ can still be substantial, even if the device contains both Rashba and Dresselhaus SO interactions, because with one subband, the D'yakonov–Perel' spin relaxation does not occur [27].

Before summarizing, let us discuss feasibility. We suggest a possible experimental set-up fabricated in a 2DEG as shown in figure 1(b), in which electrons in the dark region are depleted by the nanofabrication process. Unpolarized incident electrons from the source pass through two non-equal-length paths and converge at the drain. On the basis of the above principle, output electrons on the side of the drain are spin polarized. This spin polarized current can be measured by a quantum point contact (QPC) on the right of figure 1(b) as was done in a recent experiment [28], or by measuring the spin accumulation, and possibly by some other means. With spin polarized currents, many useful electronics devices can be designed [1]. For example, due to the spin polarization in the current, the variations of the current in response to positive and negative magnetic fields are usually unequal, so this device can work as a read head in a hard disk. It is worth mentioning that Koga *et al* recently proposed a ballistic spin interferometer [19], and they predicted the backscattering probability to depend strongly on the Rashba SO coefficient α_R. In particular, this prediction has been observed in a recent experiment [23]. In fact, our suggested device is very similar to the basic cell in the experimental device of Koga *et al* (see their figure 1 and our figure 1(a)) [19], although the functionality of our device is quite different from that of theirs. So we strongly believe the present scheme can be realized experimentally.

In summary, using the spin–orbit interaction, we propose a mesoscopic spin Mach–Zehnder interferometer for generating a spin polarized current. In this scheme, neither a magnetic field nor magnetic material is present; moreover, the spin–orbit interaction can be either uniform or non-uniform. The proposed apparatus can work not only in the ballistic regime but also in the diffusive regime. Furthermore, we find that the spin polarization and the output probability can be quite large simultaneously with suitable device parameters.

Acknowledgments

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