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Spin density induced by equilibrium spin current in a magnetic field

J Wang[1,2] **and K S Chan**[2]

[1] Department of Physics, Southeast University, Nanjing 210096, People's Republic of China
[2] Department of Physics and Materials Science, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong, People's Republic of China

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Abstract
We propose theoretically to use an external magnetic field to detect the equilibrium spin current which flows in a narrow strip. The spin current is generated by two noncollinear ferromagnets attached to the strip and the applied magnetic field is perpendicular to the plane of the strip. It is demonstrated by using the Keldysh Green's function that the interaction between the spin current and the magnetic field causes an antisymmetrical spin density at the two lateral edges of the strip. The spin density can be directly measured experimentally. Its magnitude and direction can be readily controlled by the magnetizations of the ferromagnets. The proposed scheme offers a new approach to the detection of the pure spin current.

Spin-polarized transport in nanostructures is a subject that is being studied intensively in the emerging field of spintronics [1, 2]. The aim of current spintronic research is to make spin-based electronic devices that exploit both the charge and spin degrees of freedom of electrons. Spin devices are believed to be the new generation of electronic devices with many advantages such as longer coherent lifetime, faster data processing speed, and lower electric power consumption. Some spin-based devices have already been developed and have appeared on the market, for example, giant magnetoresistance (GMR) spin-valve read heads. The generation, manipulation, and detection of spin currents are the central challenges in the spintronics field and cause intense interest in the research community.

In the last few years, much attention has been paid to the generation of pure spin current in semiconductors and great progress has been achieved [3–11]. The main generation method is spin pumping [3–7], which is usually attainable in a magnetic system or with an external magnetic field. For instance, Brataas *et al* [3] proposed the concept of a spin battery based on precessing ferromagnets for generating pure spin current. Another way to produce spin current is the spin Hall effect [8–11] in which, through spin–orbital interaction, a longitudinal electric field can produce a transverse dissipationless spin current. This method is generally referred to as a full-electric one. The spin Hall effect, either intrinsic or extrinsic, has been extensively studied recently, and spin accumulation induced by the spin Hall current at the boundaries of the sample has also been observed [12, 13]. Other methods, such as the quantum interference of laser fields in semiconductors [14] and magnon excitation in ferromagnet insulators [15], were also proposed and studied. Of particular interest is the existence of equilibrium spin current (ESC) in a noncollinear magnetic system [16–18], which does not require the application of external fields; for example, König *et al* [16] found ESC in a ferromagnetic film due to a chiral magnetic order. Many researchers [19–21] demonstrated that in noncollinear ferromagnet/ferromagnet (FM/FM) tunneling junctions ESC can flow spontaneously in the system. The phenomenon is similar to the Josephson effect, and therefore referred to as the spin Josephson effect. Even in a nonmagnetic junction, the authors [22] also found an ESC in a two-dimensional electron gas junction with spin–orbital interaction.

Although schemes for spin current generation are abundant in the literature, how to detect spin current is presently lacking attention, which may be related to the fact that pure spin current has no corresponding electric signal for direct measurement or that the definition of spin current itself is still under debate in some theoretical aspects [23]. The generic way to detect spin current is to utilize the physical effects induced by the spin current in some specific situations, such as a circular electric field, spin accumulation at sample boundaries, charge accumulation or electric current, and these induced consequences can be directly measured in experiments. For example, two groups [24, 25] observed very recently the reciprocal spin Hall effect in diffusive metals and the measured Hall voltage is a manifestation of the pure spin current.

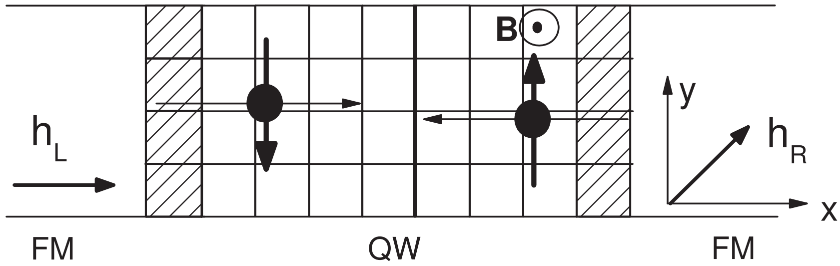

Figure 1. A schematic diagram of a two-terminal device in which two FMs are connected via a quasi-one-dimensional quantum wire. The shaded parts are the two interface barriers. The left and right magnetizations ($\mathbf{h}_L$ and $\mathbf{h}_R$) are not collinear, but both of them are in the xy-plane. The magnetic field is along the z-direction and is only applied on the QW region. An ESC can flow in the QW with a spin polarization along the z direction. Two opposite charge currents with equal magnitudes are deflected to the two edges by the Lorentz force.

In this work, we propose to use an external magnetic field to detect the ESC driven by the noncollinear magnetizations in a FM junction. The magnetic field is perpendicularly applied to a nonmagnetic narrow strip in which an ESC flows. The pure spin current consists of two equal-magnitude charge currents flowing in opposite directions; so, they feel opposite Lorentz forces under the magnetic field and, thus, an antisymmetric spin density is formed at the two lateral edges of the strip due to the ordinary Hall effect. The spin density can then be measured by optical methods in experiments. We numerically calculated the spin density in the clean limit by using the Keldysh Green's function method in real space and found that the magnitude and polarization direction of the spin density can be readily modulated by tuning the magnetizations of the FMs.

We start from the schematic model shown in figure 1. Two FM electrodes are connected by a quasi-one-dimensional quantum wire (QW), which has no magnetic order or spin–orbital interaction and thus has a well-defined spin current $\mathbf{J}_s$. The whole FM/QW/FM junction lies in the xy plane and the current direction is along the x-axis. The external perpendicular magnetic field $\mathbf{B}$ (0, 0, 1) along the z-direction is applied on the QW region; the z-direction is also set as the quantum spin axis. For simplicity, the magnetizations of the left and right FMs are chosen to be in the xy plane as $\mathbf{h}_L = (1, 0, 0)$ and $\mathbf{h}_R = (\cos\theta_R, \sin\theta_R, 0)$, respectively. These two magnetizations remain fixed in our model and the ESC will be relaxed in FM leads, i.e. the spin transfer by ESC is absorbed by the FM lattice [26]. As is well known, the ESC flowing in the QW region should be polarized along the z-direction so that the precession of the ESC around the magnetic field can be excluded. A tight-binding-type Hamiltonian of the two-terminal narrow strip can be written as $\mathcal{H} = \mathcal{H}_L + \mathcal{H}_R + \mathcal{H}_{QW} + \mathcal{H}_T$, where

$$\mathcal{H}_\alpha = \sum_{lm\mu\nu} C^\dagger_{\alpha lm\mu}(E_\alpha I + \boldsymbol{\sigma}_{\mu\nu}\mathbf{h}_\alpha)C_{\alpha lm\nu} - t\sum_{lm\mu}(C^\dagger_{\alpha l+1,m\mu}C_{\alpha lm\mu} + C^\dagger_{\alpha l,m+1,\mu}C_{\alpha lm\mu} + \text{h.c.}), \quad (1)$$

is the Hamiltonian of the left FM for $\alpha = \text{L}$, the right FM for $\alpha = \text{R}$, and the QW region for $\alpha = \text{QW}$, and

$$\mathcal{H}_T = \sum_{m\mu}(t_L C^\dagger_{Lm\mu}C_{QW,m\mu} + t_R C^\dagger_{Rm\mu}C_{QW,m\mu} + \text{h.c.}), \quad (2)$$

is the tunneling Hamiltonian between the QW and FMs without spin flip. Here $C^\dagger_{\alpha lm\mu}$ ($C_{\alpha lm\mu}$) is the creation (annihilation) operator at the site lm in the α region, μ and ν are the spin indices, and $\boldsymbol{\sigma}$ is the Pauli matrix; t is the hopping amplitude, E_α is the site energy, and I is the unit matrix. The left and right FMs are described by the Stoner model, with $\mathbf{h}_L$ and $\mathbf{h}_R$ being the corresponding magnetizations in the unit of energy and $\mathbf{h}_{QW}$ equals zero in the QW region, as mentioned above. t_L (t_R) denotes the coupling strength between the left (right) lead and the QW. The Hamiltonian above has a hard-wall potential confining the studied system.

When the magnetic field $\mathbf{B}$ is introduced in the QW region, its effects could be incorporated into the nearest-neighbor hopping amplitude by the Peierl's phase factor as

$$t'_{lm,lm+1} = t\exp(\mathrm{i}\hbar\omega_c l/2t) = (t'_{lm+1,lm})^\star;\ t'_{lm,l+1,m} = (t'_{l+1m,lm})^\star = t, \quad (3)$$

where $\omega_c = eB/mc$ is the cyclotron frequency and the corresponding cyclotron radius is estimated as $R = v_F/\omega_c$ with v_F the Fermi velocity and t' stands for the modified hopping amplitude. We choose the vector potential as $\mathbf{A} = (By, 0, 0)$, which keeps the translational symmetry of the system along the x-direction (current direction) in an infinite QW without any FM leads. The Zeeman effect from the external magnetic field is not included here since it is much smaller than one Landau level energy $\hbar\omega_c$.

In order to compute the ESC and spin density in the nonmagnetic QW region, we adopt the Keldysh Green's function method, the spin density in each site is given by

$$\mathbf{S}_{lm} = \frac{\hbar}{2}\int\frac{\mathrm{d}\omega}{2\pi}\mathrm{Tr}\{\boldsymbol{\sigma}G^<_{lm}(\omega)\}, \quad (4)$$

where the trace is over the spin space and the lesser Green's function is defined as $G^<_{lm\mu,l'm'\nu}(t,t') = \mathrm{i}\langle C^\dagger_{l'm'\nu}(t')C_{lm\mu}(t)\rangle$. In a steady state, it can be obtained by using $G^< = G^r\Sigma^<G^a$ where $G^{r(a)}$ are the retarded (advanced) Green's functions and $\Sigma^<(\omega) = \sum_{\alpha=LR} f_\alpha(\omega)(\Sigma^a_\alpha - \Sigma^r_\alpha)$ is related to the lead's Fermi-distribution function $f_{L(R)}$ and self-energy $\Sigma^{r(a)}$. Thanks to the equilibrium case considered in this work, $f_L = f_R$, it is particularly convenient to use $G^< = (G^a - G^r)f$ to simplify equation (4). The spin current through the left or right barrier is evaluated by

$$\mathbf{J}_{sL(R)} = \frac{-1}{2}\int\frac{\mathrm{d}\omega}{2\pi}\mathrm{Tr}\{t_{L(R)}\boldsymbol{\sigma}G^<_{QW,L(R)}(\omega) - t^*_{L(R)}\boldsymbol{\sigma}G^<_{L(R),QW}(\omega)\}, \quad (5)$$

where the trace is over not only the spin space but also the transverse site, and the lesser Green's function can be worked out with the same procedure as that for equation (4).

In the numerical calculation, we take the hopping amplitude t as the energy unit $t = 1$ and $E_{L(R)} = 4t$ in the FM leads, which represents the free-electron model [27]. The Fermi energy in the whole system is set as $E_F = 0.4t$ so that the Fermi wavelength $\lambda_F = 2\pi a\sqrt{t/E_F}$ is much larger than the lattice size and our model can approximate the continuum one. In the QW region, $E_{QW} = 3.6t$ is set so as to make its bandwidth larger than that of the d-electron in FMs, as well as to avoid the evanescent mode in the QW when **B** is extremely strong. It is noted that our numerical calculation can be directly generalized to discuss the disorder effect by modulating the site energy of the discrete lattice, although we study the spin density in a clean wire, because it is not expected that the spin-independent disorder affects the result qualitatively.

The exchange coupling between the noncollinear magnetizations of the two FMs can give rise to an ESC flowing through the QW with S_z polarization, $\mathbf{J}_s \sim \mathbf{h}_L \times \mathbf{h}_R$, this result is obtained at the case of low-electron transmission between the two FMs. The ESC consists of two charge currents with equal magnitude but opposite spin polarizations (along the $+z$ and $-z$ directions). In the absence of applied magnetic field, there is no spin density of S_z in the QW region. Even though the weak proximity effect exists, the in-plane magnetizations in two FMs do not lead to the S_z polarization in the QW. A three-dimensional surface plot for the spin density on the x–y plane is shown in figure 2. The antisymmetric spin polarization stems from the interplay between the ESC and the external magnetic field. The application of **B** makes the two moving charge currents with different spins have lateral deflections towards opposite lateral edges, forming an imbalance of S_z in the QW region, as shown in figure 2. We wish to point out here that although the ordinary Hall voltage does not occur because of vanishing net charge current flowing in the QW, the Hall-effect-like spin density does exist in our studied system. As **B** is weak in figure 2(a), the profile of spin density exhibits oscillations in both x and y directions. It arises from the finite size effect and magnetic field that lead to the non-uniform charge distribution. When **B** is strong enough and the transport is in the Hall regime, the spin polarization locates mainly on the two edges of the QW and almost vanishes in the middle part, indicating the formation of the edge states. Here the clear limit of the QW region is considered in the calculation. Without the momentum relaxation mechanism being involved, the obtained spin density is a pure quantum effect.

Both the ESC and magnetic field result in the spin polarization in the nonmagnetic QW. Figure 3 shows the ESC and spin density on a given site as functions of azimuthal angle θ_R of the right magnetization, which is actually the azimuthal angle difference, $\theta_R - \theta_L$, between the two FMs. The results indicate that the relative orientation between $\mathbf{h}_R$ and $\mathbf{h}_L$ can change not only magnitudes of ESC and spin density but also their signs. For weak coupling strength, e.g. $|t_L|^2 = |t_R|^2 = 0.1|t|^2$, both curves of spin current (figure 3(a)) and density (figure 3(b)) appear to be a perfect sinusoid, $\sin\theta_R$, which is consistent with the linear response result [21, 22];

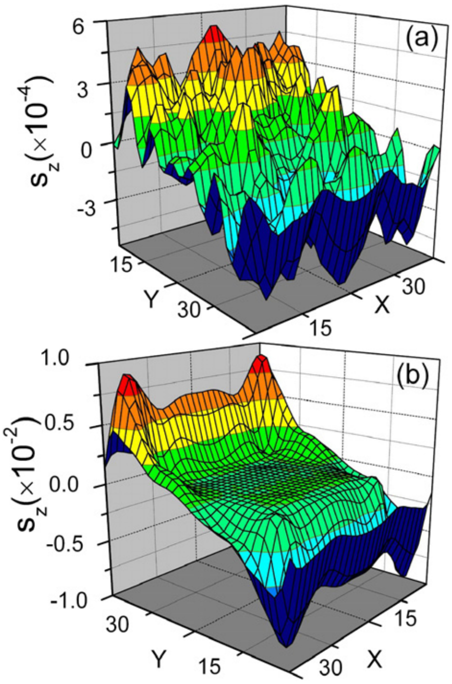

Figure 2. Spin density distribution $S_z(X, Y)$ of the QW due to the interplay of the magnetic field and the ESC flowing in the QW region. Parameters are $\mathbf{h}_R = \mathbf{h}_L = 0.3E_F$, $|t_L|^2 = |t_R|^2 = 0.6|t|^2$, $\theta_R = \pi/2$, system size $N_X \times N_Y = 30 \times 30$, $\hbar = 1$, and (a) $\mathbf{B} = 0.04t$; (b) $\mathbf{B} = 0.3t$.

(This figure is in colour only in the electronic version)

whereas in the strongly coupled case, e.g. $|t_L|^2 = |t_R|^2 = |t|^2$, the curves apparently deviate from the sinusoidal relation, as shown in figures 3(c) and (d). Such a behavior of the ESC or spin density is very similar to the Josephson current I_s as a function of macroscopic phase difference ϕ between two superconducting leads. The Josephson current is given by $I_s \sim \sin\phi$ in the weakly coupled case, which is the Ambegaokar–Baratoff result [28], and exhibits a non-sinusoidal behavior in the strongly coupled case, which is the Kulik–Omel'yanchuk result [29].

The applied magnetic field and the spin polarization of ESC along the z-direction are parallel to each other in the discussion above, however, it is not a prerequisite to form spin accumulation at lateral edges of the strip. For instance, when the spin polarization of ESC has x or y components (spin current is a tensor in reality), and the applied magnetic field is still along the z-direction, the nonlinearity between ESC spin polarization and external magnetic field will result in spin precession, then the spin polarization is no longer uniform in spin space, the spin accumulation itself still exists in the nonmagnetic QW and its polarization may be along x- and y-directions due to spin precession. More importantly, the antisymmetric property of spin density in the strip along the transverse (y) direction remains unchanged, as well as the symmetry along the x-direction. When the applied magnetic field **B** is reversed, the induced spin density in the strip is expected to change its sign, $\mathbf{S}(\mathbf{B}) = -\mathbf{S}(-\mathbf{B})$, because the Lorentz force will invert for a given moving charge, too, so that the spin polarization at the lateral edge of the strip will

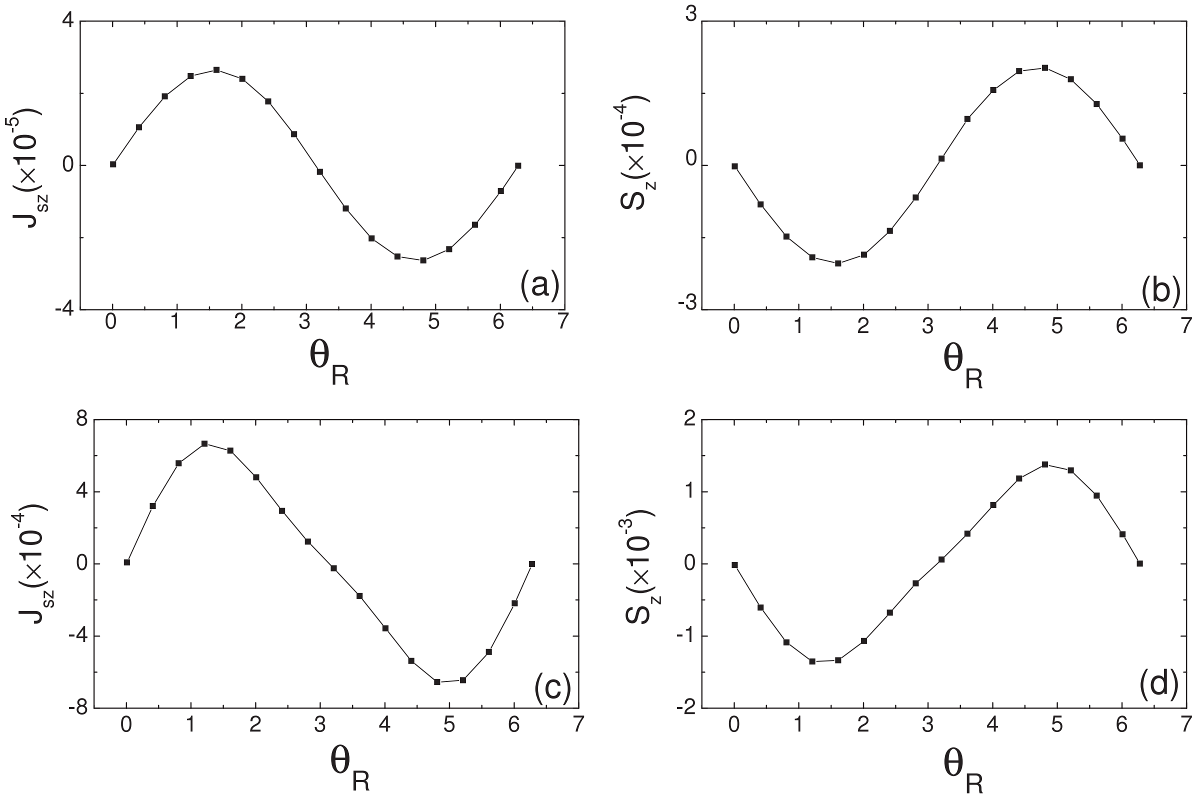

Figure 3. The spin current ((a), (c)) and the spin density ((b), (d)) as a function of the azimuthal angle θ_R for different coupling strengths, $|t_L|^2 = |t_R|^2 = 0.1|t|^2$ in (a) and (b), and $|t_L|^2 = |t_R|^2 = |t|^2$ in (c) and (d). Other parameters are the same as those in figure 2(a). The spin density is taken on the lattice site (15, 3).

flip to the opposite one. This indicates that the spin current remains invariant with the magnetic field inversion, $\mathbf{J}_s(-\mathbf{B}) = \mathbf{J}_s(\mathbf{B})$, which derives from the fact that the ESC itself does not break time-reversal symmetry when it occurs spontaneously between two noncollinear FMs: this is different from the Josephson current flowing in the superconductor junction. The properties of ESC can help the experimental measurement of it.

In summary we have shown that the flow of a pure spin current in a two-terminal strip can induce transverse spin density when an external magnetic field is perpendicularly applied on the strip. The pure spin current is generated by two noncollinear FMs. Further, our conclusion is not limited to the ESC but also applies to other pure spin currents arising from different mechanisms. The spin density locates antisymmetrically on two lateral edges of the strip due to the ordinary Hall effect, and its magnitude and direction can be conveniently modulated by two magnetizations of FMs. Our calculation may shed light on the experimental measurement of pure spin currents with various spin polarizations.

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