Physics Letters A 379 (2015) 3114–3118

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Conversion of equilibrium spin current into charge current through a quantum-dot spin valve subject to circularly polarized field

Feng Liang [a,*], Ben-Ling Gao [a], Guang Hu [a], Yu Gu [b], Ning Xu [c]

[a] Department of Physics, Huaiyin Institute of Technology, Huaian 223003, China
[b] Department of Physics and Siyuan Laboratory, Jinan University, Guangzhou 510632, China
[c] The School of Mathematics and Physics, Yancheng Institute of Technology, Yancheng 224051, China

ARTICLE INFO

Article history:
Received 16 April 2015
Received in revised form 14 September 2015
Accepted 15 September 2015
Available online 26 September 2015
Communicated by R. Wu

Keywords:
Spintronics
Equilibrium spin current
Spin valve
Circularly polarized field
Nonequilibrium Green's function method

ABSTRACT

We theoretically investigate the electron transport through a quantum-dot spin valve subject to a circularly polarized field. It is shown that the original equilibrium spin current arising from the spin Josephson effect can be converted to a charge current by the circularly polarized field. Numerical calculations demonstrate that the sign and the magnitude of the equilibrium spin current can both be deduced from the induced charge current. Moreover, the dependence of the induced charge current on the system parameters is also studied and the most important finding is that for most choices of the system parameters the induced charge current is large enough to be measured by present technology. Therefore, our findings offer a promising way to detect the equilibrium spin current in spin valve systems.

1. Introduction

Since the giant magneto-resistance effect [1,2] was discovered over two decades ago, much effort has been devoted to the new emerging subfield of condensed matter physics spintronics [3–6]. Spintronics aims at designing future spin-based devices that utilize the spin degrees of freedom of electron instead of the charge one to store, process and transfer information. Similar to the role charge current plays in conventional charge-based devices, spin current consisting of electronic currents with opposite spins flowing in opposite directions is essential for the function of spin-based devices. Hence, for the development of spintronics generation and detection of spin current in solid-state systems is necessary. To date, many methods for generating spin current have been put forward. These methods include spin injection from ferromagnetic (FM) materials into nonmagnetic ones [7–11], spin pumping with a time-dependent or inhomogeneous magnetic field [12–16], optical spin orientation [17–20], spin Hall effect [21,22], spin interference in multi-terminal mesoscopic devices [23–26], spin Seebeck effect manipulated by temperature gradient [27–32] and spin Josephson effect in spin valve systems [33–35]. The spin Josephson effect is an analogy to the well-known Josephson effect, which refers to the fact that a pure spin current can spontaneously flow through a spin valve system with noncollinear magnetizations without any bias. Such an equilibrium spin current (ESC) has been verified to be determined by $\vec{M}_L \times \vec{M}_R$ with $\vec{M}_L$ and $\vec{M}_R$ being the magnetic moments in two electrodes of the system [33], indicating that the ESC is the result of the exchange coupling between the two magnetic moments.

Up to now, there have also been some proposals for detecting spin current in the literature. One of the most important examples of the electrical schemes is the use of inverse spin Hall effect. For example, a research group [36] reported the first observation of inverse spin Hall effect in a simple metal and the electric-potential difference between the electrodes connected to the metal is a manifestation of the injected pure spin current. Other typical schemes for the detection of spin current include measuring the spin torque transferred by a spin current flowing through a ferromagnetic/normal metal tunnel junction [37] and observing the spin accumulation at the sample boundaries induced by the spin Hall current [38]. In addition, Wang et al. [39] proposed to detect the spin Josephson effect induced ESC in a narrow strip attached to two ferromagnets by using a static magnetic field. The applied magnetic field exerts opposite Lorentz forces on the two spin component currents of the ESC and thus deflects them to the opposite lateral edges of the strip. Then an antisymmetrical spin density forms at the two edges, which can be measured to deduce the ESC. Therefore, in this proposal the strip should be long enough to

* Corresponding author.
E-mail address: bd10583@163.com (F. Liang).

http://dx.doi.org/10.1016/j.physleta.2015.09.037

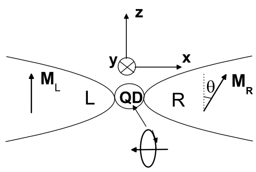

Fig. 1. Schematic diagram for a quantum-dot spin valve system subject to a CPF. The quantum dot is attached to two ferromagnetic electrodes. The magnetic moments of the two electrodes lie in the xz-plane and the circularly polarized field is propagating along the y-direction.

make the deflected electrons arrive at the lateral edges before entering into the electrodes. However, a long strip can also decrease the ESC significantly since the exchange coupling between the ferromagnets is sensitive to their distance. This dilemma obviously influences the feasibility of this detection scheme.

In this work, we propose a new scheme to detect the spin Josephson effect based on a FM-quantum dot (QD)-FM system exposed to a circularly polarized field (CPF), where the decrease of the spin current is avoided. Due to the spin Josephson effect, an ESC originally exists in the FM-QD-FM system, which is composed of two spin component currents flowing in opposite directions with equal magnitudes and thus is a pure spin current not accompanied with any charge current. However when a CPF propagating along the spin polarization direction of the spin current is applied to the QD, the symmetry between the spin-up and spin-down currents in the original ESC is destroyed by a spin flip effect arising from the CPF and thus a nonzero charge current emerges which can be measured to detect the ESC. Based on the nonequilibrium Green's function method, we numerically investigated the induced charge current and revealed some interesting properties of the induced charge current which are dependent on the system parameters.

The rest of this paper is organized as follows. In the next section, we propose the theoretical model and derive the general formula of the induced charge current. Section 3 presents the detailed numerical calculations. Finally, a brief conclusion is given in the last section.

2. Physics model and formula

The FM-QD-FM system we consider is schematically depicted in Fig. 1. It consists of two FM electrodes coupling via a QD. The magnetization of the electrodes lies in the xz plane and the current is flowing in the x-axis. The magnetization direction of the left FM electrode is pointing to the z-axis which is also taken as the spin quantum axis, while the magnetization direction of the right FM electrode deviates from the z-axis with an angle θ. According to Refs. [33–35], a pure spin current can flow through the studied system with zero bias and the spin polarization direction of the spin current should point to the y-axis. To convert the spin current into a charge current, we introduce a CPF to irradiate the QD and the propagation direction of the field is also along the y-axis. Then the Hamiltonian of the studied system is given by

$$H = \sum_{\alpha=L,R} H_\alpha + H_d + H_T + H'(t), \tag{1}$$

$$H_\alpha = \sum_{k\sigma} \varepsilon_{k\alpha\sigma} C^\dagger_{k\alpha\sigma} C_{k\alpha\sigma}, \tag{2}$$

$$H_d = \sum_{\sigma} \varepsilon_d d^\dagger_\sigma d_\sigma, \tag{3}$$

$$H_T = \sum_{k\sigma} [t_{Ld} C^\dagger_{kL\sigma} d_\sigma + t_{Rd}(\cos\frac{\theta}{2} C^\dagger_{kR\sigma} - \sigma \sin\frac{\theta}{2} C^\dagger_{kR\bar{\sigma}}) d_\sigma + h.c.], \tag{4}$$

$$H'(t) = \gamma (d^\dagger_\uparrow \; d^\dagger_\downarrow) \begin{pmatrix} \sin\omega t & \cos\omega t \\ \cos\omega t & -\sin\omega t \end{pmatrix} \begin{pmatrix} d_\uparrow \\ d_\downarrow \end{pmatrix}. \tag{5}$$

H_α describes the FM electrode α ($\alpha = L, R$) within the Stoner model where $C^\dagger_{k\alpha\sigma}$ ($C_{k\alpha\sigma}$) is the creation (annihilation) operator of spin-σ electrons ($\sigma = \pm = \uparrow, \downarrow$) with momentum k in electrode α and $\varepsilon_{k\alpha\sigma} = \varepsilon_{k\alpha} + \sigma M_\alpha$ is the single-electron energy of spin polarized conducting electrons in the molecular field $\mathbf{M}_\alpha$. H_d models the QD with the single-level Anderson impurity model without the consideration of Coulomb interaction for simplicity where $d^\dagger_\sigma$ (d_σ) represents the creation (annihilation) operator of spin-σ electron in the QD and ε_d denotes the spin-degenerate single electron energy. H_T describes electron tunneling between the FM electrodes and the QD with $t_{\alpha d}$ ($\alpha = L, R$) being the tunneling coefficient. The last time-dependent term of the model Hamiltonian $H'(t)$ is from the applied CPF. The CPF is propagating along the y-axis and hence acts like a magnetic field rotating in the xz (not xy) plane here. The interaction between a magnetic field $\vec{B}$ and the electron spin (usually denoted by the Pauli matrix $\vec{\sigma}$) is proportional to $\vec{\sigma}.\vec{B}$, so $H'(t)$ can be written as Eq. (5) with γ and ω denoting the strength and frequency of the CPF respectively.

Using the standard Keldysh nonequilibrium Green's function technique, the spin component current tunneling from the left electrode $I_{L\sigma}(t)$ can be derived as [40]

$$I_{L\sigma}(t) = -\frac{2e}{\hbar} Re \int dt_1 [G^r(t,t_1)\Sigma^<_L(t_1,t) + G^<(t,t_1)\Sigma^a_L(t_1,t)]_{\sigma\sigma}. \tag{6}$$

Here G^r and $G^<$ are the retarded and lesser-than Green's functions of the QD respectively, whose matrix elements in spin space can be defined as $G^r_{\sigma\sigma'}(t,t') = -i\theta(t-t')\langle[d_\sigma(t), d^\dagger_{\sigma'}(t')]_+\rangle$, $G^<_{\sigma\sigma'}(t,t') = i\langle d^\dagger_{\sigma'}(t') d_\sigma(t)\rangle$ with $\langle\cdots\rangle$ and $[\cdots]_+$ representing quantum statistical average and anticommutator operation respectively. $\Sigma^{a(r,<)}_\alpha = \sum_k |t_{\alpha d}|^2 g^{a(r,<)}_{k\alpha k\alpha}$ is the advanced (retarded, lesser) self-energy contributed by electrode α, where $g^{a(r,<)}_{k\alpha k\alpha}$ denotes the advanced (retarded, lesser) Green's functions of electrode α without coupling with the center region. Performing a double-time Fourier transformation and extending the integration range of dt_1 to $[-\infty, +\infty]$ [41,42], the time-averaged electronic current with σ-spin from the left electrode can be written as

$$I_{L\sigma} = -\frac{e}{\hbar}\frac{1}{N\tau} Re \int \frac{dE_1}{2\pi}\frac{dE_2}{2\pi} [G^r(E_1,E_2)\Sigma^<_L(E_2,E_1) + G^<(E_1,E_2)\Sigma^a_L(E_2,E_1)]_{\sigma\sigma}, \tag{7}$$

where $\tau = 2\pi/\omega$, $N \to \infty$ and since no time-varying potential exists in the electrodes we can have $\Sigma^{<(a)}_L(E_2,E_1) = 2\pi\delta(E_2 - E_1)\Sigma^{<(a)}_L(E_1)$. Then Eq. (7) becomes

$$I_{L\sigma} = -\frac{e}{h}\frac{1}{N\tau} Re \int dE [G^r(E,E)\Sigma^<_L(E) + G^<(E,E)\Sigma^a_L(E)]_{\sigma\sigma}. \tag{8}$$

In the above equation, the retarded Green's G^r obeys the well-known Dyson equation [43]

$$G^r(t,t') = G^{r0}(t,t') + \int dt_1 G^{r0}(t,t_1) H'(t_1) G^r(t_1,t'), \tag{9}$$