

# Inverse Spin Hall Effect in Two-Terminal Device with Rashba Spin-Orbit Coupling\*

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(Received May 11, 2009; Revised September 17, 2009)

**Abstract** We report a theoretic study on the inverse spin-Hall effect (ISHE) in a two-terminal nano-device that consists of a two-dimensional electron gas (2DEG) with Rashba spin-orbit coupling (RSOC) and two ideal leads. Based on a two-site toy model and Keldysh Green's function method, we derive an analytic result of ISHE, which shows clearly that a nonzero transverse charge current stems from the combined effect of the RSOC, the spin bias, and its spin polarization direction in spin space. Our further numerical calculations in a larger system other than two-site lattice model demonstrate that the transverse charge current, dependent on the strength of the RSOC, the Fermi energy of the system, as well as the system size, can exhibit oscillating behavior and even reverse its sign due to Rashba spin precession. These properties may be helpful for efficient detection of the spin current (spin bias) by measuring the transverse charge current in a spin-orbital coupling system.

**PACS numbers:** 73.23.-b, 72.25.Dc, 71.70.Ej

**Key words:** spin Hall effect, spin-orbital coupling, inverse spin-Hall effect, Keldysh Green's function

## 1 Introduction

Spintronics, a new subfield of the condensed matter physics, has been studied intensively for a decade because of its enormous application potentials in quantum information and quantum computing.<sup>[1–3]</sup> Currently, many great challenges still remain in this exciting field, such as how to achieve efficient injections of spins into nonmagnetic semiconductors, manipulation and measurement of the spin current. Various methods have been proposed to realize injections of spins using ferromagnetic semiconductor.<sup>[4–5]</sup> For practical use, however, the Curie temperatures of ferromagnetic semiconductors are still too low. As a solution to this spin injection, the spin Hall effect (SHE) has been hotly discussed in last several years, which was proposed by Murakami *et al.*<sup>[6]</sup> in a 3D p-doped semiconductor and Sinova *et al.*<sup>[7]</sup> in 2D electron gas (2DEG) with Rashba spin orbital coupling (RSOC). The SHE is characterized by the transverse non-dissipation spin current or spin accumulation at boundary induced by a longitudinal electric field/current. The spin Hall current is a pure spin current without any charge current that spin-up and spin-down electron current move along opposite direction. This SHE from the topological band structure was referred to as intrinsic SHE, another type of SHE predicted in 1971 by Dyakonov and Perel<sup>[8]</sup> was called extrinsic one,<sup>[9]</sup> because it is driven by impurity scattering with SOC. For intrinsic SHE, it is commonly agreed now that it is absent in 2D system with any weak disorder for linear spin orbital coupling whereas it can survive for sophisticated SOC or in a finite mesoscopic system.<sup>[10–11]</sup>

On the aspects of experiment, Kato *et al.*<sup>[12]</sup> reported the first experimental observation of the SHE induced spin accumulation near the sample boundaries via the magneto-optical Kerr effect in GaAs semiconductor systems. The spin-orbit interaction responsible for the SHE is also expected to cause the inverse process of the SHE (ISHE), which can convert a longitudinal spin current into a transverse charge current and thus a Hall voltage forms at two lateral edges of an open system. The induced charge current (Hall voltage) can be exploited to detect not only the magnitude but also the spin-polarization direction of the spin current because the induced charge current  $\mathbf{J}_c$ , the injected spin current  $\mathbf{J}_s$ , and the spin-polarization vector of the spin current  $\mathbf{s}$  satisfy the relation  $\mathbf{J}_c \propto \mathbf{J}_s \times \mathbf{s}$ .<sup>[13–14]</sup> In experiments, the Hall voltage via this ISHE has been recently observed in diffusive metals.<sup>[13–15]</sup> On the theoretic aspect, ISHE has also been studied in mesoscopic systems with RSOC<sup>[16–18]</sup> together with SHE, and the Onsager reciprocal relation between them was confirmed. So far, only a few theoretical works focus on ISHE and they are limited to numerical calculations.

To see clearly what factors affect the ISHE, we will in this work study the ISHE in detail and especially, present some analytical result of the transverse charge current induced by the ISHE. A two-terminal device is considered that a 2D electron gas with RSOC is connected with two ideal leads, the longitudinal spin current flowing through the device is driven by an external spin bias, satisfying  $\mu_{L\uparrow} + \mu_{L\downarrow} = \mu_{R\uparrow} + \mu_{R\downarrow} = 0$ ,  $\mu_{L\uparrow} = \mu_{R\downarrow}$ ,  $\mu_{R\uparrow} = \mu_{L\downarrow}$ ,<sup>[16,19]</sup> so that no charge current can be driven

\*Supported by National Natural Science Foundation of China under Grant No. 10704016, and National Natural Science Foundation of Jiangsu Province under Grant No. BK2007100, and New Teacher Fund of Ministry of Education of China under Grant No. 20070286036

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to flow. A transverse charge current is expected to occur as the spin-orbit coupling exists in the scattering region. Based on Keldysh Green's function, we firstly derived out the charge current that satisfies the relation  $\mathbf{J}_c \propto \mathbf{J}_s \times \mathbf{s}$ , and then we performed the further numerical calculation and found that the charge current is drastically dependent on the strength of the RSOC, the electron Fermi energy, as well as the system size.

## 2 Model and Methods

The system we considered consists of a scattering region of a 2DEG with RSOC connected to two semi-infinite leads. The leads are all ideal and nonmagnetic, i.e., no spin-orbit coupling or other kinds of spin-flip processes are present in the leads, moreover, the coulomb interaction is absent in both leads and 2DEG. When the leads are applied by the spin bias, a pure spin current is flowing in the longitudinal direction. The spin-orbit coupling in the scattering region can exert an electromotive force on the spin-up and spin-down electrons in the opposite direction perpendicular to the spatial direction of the pure spin

current, and consequently, a transverse charge current is induced in the central scattering region. If the leads are connected to the lateral edge of the sample, the transverse charge current will flow out. The spin current flows along  $x$ -axis and the transverse charge current is flowing along  $y$ -axis, the normal of the 2DEG is along  $z$ -axis and it is also set as the quantum spin axis.

The central region can be described by the Hamiltonian  $\mathcal{H} = \mathbf{p}^2/2m^* + (\alpha/\hbar)(\sigma_x p_y - \sigma_y p_x)$ , where the first term is the kinetic energy of free electron, and the second term describes the RSOC with  $\alpha$  the Rashba coupling constant,  $m^*$  is the electron effective mass,  $p_x$  and  $p_y$  are the two components of the momentum operator  $\mathbf{p}$ ,  $\sigma_x$  and  $\sigma_y$  are the Pauli matrices. In the studied system,  $\alpha$  is nonzero only in the central region and it can be directly modulated by an external gate voltage or an electric field perpendicular to the 2DEG plane.<sup>[20–21]</sup> In the site-representation, the Hamiltonian of a tight-binding type of the whole system is given by

$$\mathcal{H} = \mathcal{H}_{\text{Leads}} + \mathcal{H}_{\text{2DEG}} + \mathcal{H}_T, \quad (1)$$

$$\mathcal{H}_{\text{Leads}} = \sum_{ij\sigma} \varepsilon_{ij\sigma} C_{ij\sigma}^\dagger C_{ij\sigma} - t \sum_{ij\sigma} (C_{i+1,j\sigma}^\dagger C_{ij\sigma} + C_{i,j+1,\sigma}^\dagger C_{ij\sigma} + \text{c.c.}), \quad (2)$$

$$\begin{aligned} \mathcal{H}_{\text{2DEG}} = & \sum_{ij\sigma} \varepsilon_{ij\sigma} C_{ij\sigma}^\dagger C_{ij\sigma} - t \sum_{ij\sigma} (C_{i+1,j\sigma}^\dagger C_{ij\sigma} + C_{i,j+1,\sigma}^\dagger C_{ij\sigma} + \text{c.c.}) \\ & - t_{\text{so}} \sum_{ij\sigma\sigma'} [C_{i+1,j\sigma}^\dagger (i\sigma_y)_{\sigma\sigma'} C_{ij\sigma'} - C_{i,j+1,\sigma}^\dagger (i\sigma_x)_{\sigma\sigma'} C_{ij\sigma'} + \text{c.c.}], \end{aligned} \quad (3)$$

$$\mathcal{H}_T = \sum_{j\sigma} [(t'_L C_{j\sigma,L}^\dagger C_{j\sigma,2\text{DEG}} + t'_R C_{j\sigma,R}^\dagger C_{j\sigma,2\text{DEG}}) + \text{c.c.}]. \quad (4)$$

Here  $\mathcal{H}_{\text{Leads}}$  describes the left and right ideal lead within a non-interacting electron gas model.  $\mathcal{H}_{\text{2DEG}}$  is the Hamiltonian of the central region with RSOC; the last Hamiltonian  $\mathcal{H}_T$  models the coupling between the leads and the central region.  $C_{ij\sigma}^\dagger$  ( $C_{ij\sigma}$ ) is the creation (annihilation) operator of an electron at site  $(i,j)$  with spin  $\sigma = \uparrow, \downarrow$ ,  $\varepsilon_{ij\sigma} = 4t$  is the site energy,  $t = \hbar^2/(2ma^2)$  is the hopping energy between two nearest-neighbored lattice site with the lattice constant  $a$ .  $t_{\text{so}} = \alpha/2a$  is the RSOC strength.  $t'_{L(R)}$  is the hopping strength between the left (right) lead and the scattering region, which is independent of spin so that no spin-flip effect occurs when electrons tunnel through the interfaces. It also represents the strength of the interface barrier between the leads and the scattering region.

It is noted that since the translational symmetry was held in the  $y$  direction, the electric momentum  $k_y$  is a good quantum number and summation in Eqs. (2) and (3) over  $j$  sites can be transformed to the  $k$ -space,<sup>[22–23]</sup> i.e.,

$$\begin{aligned} \mathcal{H}_{\text{Leads}} = & \sum_{i\sigma} [4t - 2t \cos(k_y a)] C_{i\sigma}^\dagger C_{i\sigma} - \sum_{i\sigma} (t C_{i+1,\sigma}^\dagger C_{i\sigma} + \text{c.c.}), \\ \mathcal{H}_{\text{2DEG}} = & \sum_{i\sigma} [4t - 2t \cos(k_y a)] C_{i\sigma}^\dagger C_{i\sigma} - \sum_{i\sigma} (t C_{i+1,\sigma}^\dagger C_{i\sigma} + \text{c.c.}) \\ & - \sum_{i\sigma\sigma'} [t_{\text{so}} C_{i+1,\sigma}^\dagger (i\sigma_y)_{\sigma\sigma'} C_{i\sigma'} + \text{c.c.} + 2t_{\text{so}} \sin(k_y a) C_{i\sigma}^\dagger (\sigma_x)_{\sigma\sigma'} C_{i\sigma'}]. \end{aligned} \quad (6)$$

This transformation will reduce our numerical calculations greatly in a system with a finite size along the  $y$ -direction, however, this reduction does not alter our model itself, a 2D system in essence. We focus on the transverse charge current induced by applying a spin bias

$\sigma V_s$  on left and right leads, so that the spin-dependent chemical potential in one lead is unequal, i.e.  $\mu_{L,n\uparrow} = -\mu_{L,n\downarrow} = -\mu_{R,n\uparrow} = \mu_{R,n\downarrow} = eV_s/2$ , where  $n$  denotes the spin-polarization direction, which in terms of the unit vector of the Cartesian coordinates should be described

as  $(\sin\theta \cos\phi\vec{x}, \sin\theta \sin\phi\vec{y}, \cos\theta\vec{z})$ . It is noted that spin bias is diagonal as above in the spin eigen-space, and otherwise the non-diagonal terms exist. By using the local charge density operator  $\rho(\mathbf{r}, t) = e\varphi^\dagger(\mathbf{r}, t)\varphi(\mathbf{r}, t)$ , we can obtain the continuity equation of charge current density  $\partial\rho/\partial t + \nabla \cdot \mathbf{J}_c = 0$  where the charge current density  $\mathbf{J}_c = e \cdot \text{Re}(\varphi^\dagger \mathbf{v} \varphi)$  with  $\varphi(\mathbf{r}, t)$  being a two-component wave function in the spin space and  $\mathbf{v}$  is the velocity operator. In the semiclassical approximation, the charge current density along the transverse direction ( $y$ -axis) can also be expressed as

$$J_c = \frac{e}{iW} \sum_{k_y} \int \frac{dE}{2\pi} \text{Tr} [v_y G^<(E, k_y)], \quad (7)$$

with

$$v_y = \frac{1}{\hbar} \frac{\partial \hat{H}}{\partial k_y}, \quad (8)$$

where the lesser Green's function is defined as  $G^<(xt, x't') = i\langle \varphi^\dagger(x't')\varphi(xt) \rangle$ , with  $\langle \dots \rangle$  denoting the quantum statistical average.  $W$  is the transverse width of the system, the trace is over the spin indices. The lesser Green's function can be evaluated by the Keldysh equation  $G^< = G^r \Sigma^< G^a$ , where the retarded and advanced Green's function of the system  $G^{r(a)}$  with the leads taken into account through the self-energy  $\Sigma_{p,\sigma}^{r(a)}(i, j)$  has the form  $G^{r(a)}(i, j) = [E\delta_{ij} - \mathcal{H}_{\text{DEG}} - \sum_{p,\sigma} \Sigma_{p,\sigma}^{r(a)}(i, j)]^{-1}$ ,  $G^r$  and  $G^a$  are conjugate to each other  $G^r = [G^a]^\dagger$ ;  $\Sigma_{p,\sigma}^{r(a)}(i, j) = |t'_p|^2 g_p^{r(a)}(i, j)$  is the self-energy arising from the coupling of the SOC central region with the lead- $p$ ,  $g_p^{r(a)}$  represents the Green's function for an isolated lead- $p$  and  $t'_p$  is the coupling matrix of adjacent sites between lead- $p$  and the central region. The surface Green's function can be obtained by the expression

$$g_p^r(i, j) = -\frac{1}{t} \sum_m \chi_m(p_i) \exp[ik_{xm}a] \chi_m(p_j),^{[24]}$$

where  $k_{xm}$  denotes the longitudinal wave vector in the lead,  $\chi_m(p_i)$  denotes the transverse spatial wave function of mode  $m$  in lead- $p$ . The longitudinal wave vector is determined by the following dispersion relation:

$$J_c = \frac{4e}{h} t_{\text{so}}^2 \cos\theta \sum_{k_y} \int dE \frac{1}{|A|^2} \Gamma(E) (f_{L\uparrow}(E) - f_{L\downarrow}(E)) \sin^2(k_y a) \left[ 8t^2 R (R^2 - t^2 - \frac{1}{4}\Gamma^2) \right], \quad (12)$$

with

$$A = [-[E - \Sigma_L^r - 4t + 2t \cos(k_y a)]^2 + t^2 + t_{\text{so}}^2 + 4t_{\text{so}}^2 \sin^2(k_y a)]^2 - 16t_{\text{so}}^2 t^2 \sin^2(k_y a), \quad (13)$$

$$R = E - 4t + 2t \cos(k_y a), \quad (14)$$

where the summation over  $k_y$  denotes the contribution of all transverse modes to the charge current, and  $k_y$  is assumed to be conserved when the electron moves through the interface between the scattering region and the leads. According to the equations above, it is clear that the

$E = \varepsilon_m + 2t[1 - \cos(k_{xm}a)]$ , where  $\varepsilon_m$  is the eigenenergy of the  $m$ -th transverse mode and  $E$  is the energy of the incident electron, here  $m$  can be actually replaced by  $k_y$  as the transverse mode index. The self-energy  $\Sigma^<(E)$  can be obtained by  $\Sigma^<(E) = \sum_{p,\sigma} i\Gamma_{p,\sigma}(E) f_p(E - \mu_{p,\sigma})$  where  $f_p(E - \mu_{p,\sigma})$  is the Fermi-Dirac distribution function for electrons with spin  $\sigma$  in the lead- $p$ ,  $\mu_{p,\sigma}$  is the spin-dependent chemical potential and the line width function  $\Gamma_{p,\sigma} = i(\Sigma_{p,\sigma}^a - \Sigma_{p,\sigma}^r)$  describes the coupling strength between lead- $p$  and the center scattering region. For simplicity, we assume  $\Gamma_L(E) = \Gamma_R(E) = \Gamma(E)$  here.

As stated early, when the spin polarization of the spin bias is along the  $z$ -direction, the spin-dependent Fermi-Dirac distribution function is diagonal in spin space. Since in this work the spin-polarization of the spin bias can be oriented in any  $\hat{n}$  direction, we need to rotate the diagonal Fermi function  $f_p(E - \mu_{p,\sigma})$  in its eigen-spin space  $\hat{n}$  to the spin space  $f_p(E, \vec{n})$  with the  $z$ -axis being the quantum axis, the unitary transformation is given as

$$f_p(E, \vec{n}) = U f_p(E - \mu_{p,\sigma}) U^\dagger, \quad (9)$$

$$f_p = \begin{pmatrix} f_{p\uparrow} & 0 \\ 0 & f_{p\downarrow} \end{pmatrix}, \quad (10)$$

$$U = \begin{pmatrix} \cos \frac{\theta}{2} & \sin \frac{\theta}{2} e^{-i\varphi} \\ -\sin \frac{\theta}{2} e^{i\varphi} & \cos \frac{\theta}{2} \end{pmatrix}, \quad (11)$$

where  $f_{p\sigma}$  is spin-dependent Fermi-Dirac distribution function of the electron in the lead- $p$ .

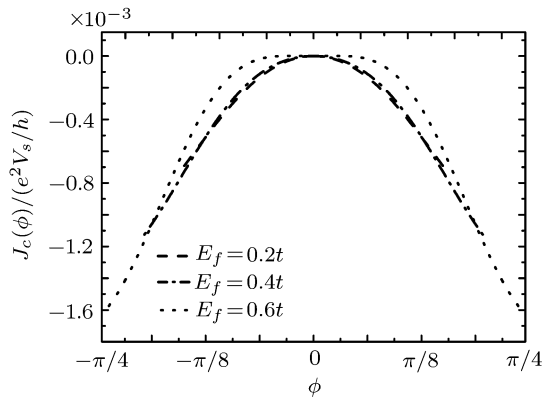
### 3 Results and Discussion

To simplify the analytical derivation, we firstly make use of the two lattice-point model to calculate the transverse charge current induced by ISHE, i.e., only two lattice sites along the  $x$ -direction in the central region is considered. This allows one to work out the Green's function  $G^{r,a,<}$  analytically. With direct algebra, the resultant expression up to the  $t_{\text{so}}^2$  order for the transverse charge current in Eq. (7) is given by

ISHE or a transverse charge current  $J_c$  can indeed exist in the studied system and that the longitudinal spin current (spin bias) and the RSOC are two prerequisites for the generation of the charge current. In addition, Eq. (12) also shows that the charge current  $J_c$  is proportional to

$\cos\theta$ . This result is consistent with the well known relation  $\mathbf{J}_c \propto \mathbf{J}_s \times \mathbf{s}$ , indicating that the spin polarization of the spin current also plays a crucial role in ISHE. This indicates that the longitudinal spin current with spin polarization only along  $z$  axis,  $J_{\sigma_z}$ , can lead to the ISHE, and it is indeed a reciprocal process to the SHE that a charge current can induce only  $\sigma_z$  spin current.

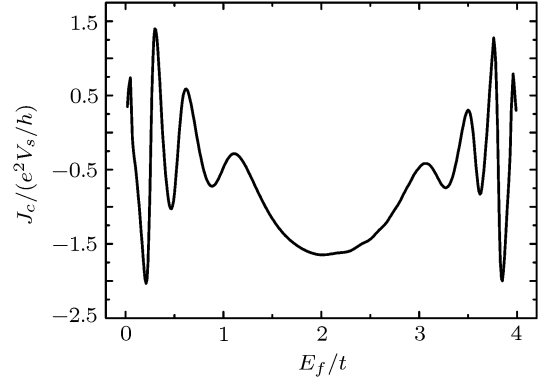
In the following, we present the numerical results about the transverse charge current. Here we focus on the linear transport regime that the spin bias is very weak  $V_s \rightarrow 0$ , then the integration over energy in Eq. (12) can be solved and the induced charge current is proportional to  $V_s$ . In the numerical calculation, the hopping energy  $t$  is taken as the energy unit  $t = 1$ , in the most cases, the strength of RSOC in the central scattering region is around  $t_{so} = 0.1t$  according to experimental measurements,<sup>[20]</sup> the temperature is set as  $T = 0$  K. According to Eq. (12), we firstly present the distribution profile of transverse charge current  $J_c$  over the transverse momentum  $k_y$ , which can also be regarded as the incident angle ( $\phi$ ) of the electron moving through the interface between leads and the central RSOC region. It is shown that  $J_c(\phi)$  vanishes for  $k_y = 0$ , which can actually be seen from Eq. (12). This confirms the common agreement that the SHE can not occur for a strict 1D RSOC system. Due to the even function of  $J_c(\phi)$  over  $k_y$ , the summation over the transverse modes will bring out the nonzero charge current. With increase of Fermi energy  $E_f$ , the  $J_c$  increases a little for the involved mode number as  $E_f$  grows. Here it is pointed out that the cut-off angle  $\phi_c$  in the calculation is determined by the Fermi energy via the energy dispersion in the lead,  $\varepsilon_m = 2t(1 - \cos(k_y a))$ .



**Fig. 1** The transverse charge current  $J_c(\phi)$  as a function of angle  $\phi = k_y a$  for different Fermi energy  $E_f = 0.2t, 0.4t, 0.6t$  with the sample size  $L = 2a$  in two lattice sites model. The other parameters are  $\theta = \varphi = 0$ ,  $t_{so} = 0.1t$ .

We proceed to examine the charge current dependence on the system parameters in a much larger system other

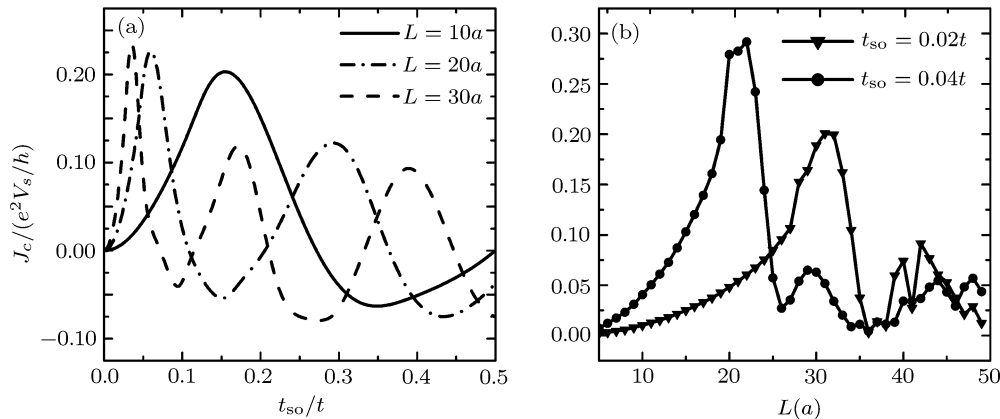
than two sites model above. Here the numerical procedures are employed to solve the Green's function  $G^r$  and  $G^<$  in Eq. (7) to calculate  $J_c$ . For a fixed sample size  $L = 50a$  in the middle scattering region, the charge current  $J_c$  induced by the ISHE is plotted in Fig. 2 as a function of the Fermi energy  $E_f$ . The charge current  $J_c$  is symmetric over the band center  $E_f = 2t$  and exhibits oscillation at the two edges of band. This indicates that the charge current has the electron-hole symmetry, whereas the spin Hall current induced by longitudinal electric field possesses the electron-hole antisymmetry property. The charge current oscillates at the edges of energy band and varies smoothly at the band center, this originates from the dense levels near band edge and much sparse levels around  $E_f$ , and it is similar to the VanHove singularity in the density states of 1D model.



**Fig. 2** The charge current  $J_c$  vs the Fermi energy  $E_f$  for the spin-orbit coupled strength  $t_{so} = 0.1t$ , the other parameters are  $L = 50a$ ,  $\theta = \varphi = 0$ .

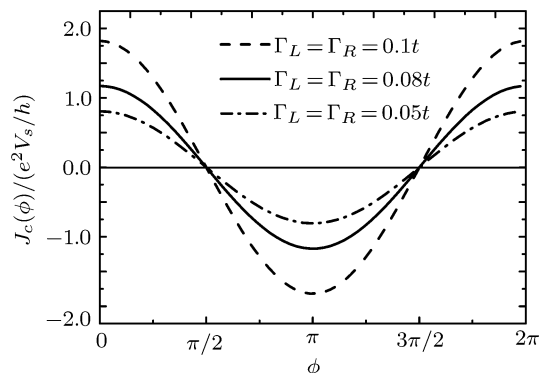
The RSOC constant can be modulated in the experiment by a perpendicular electric field to 2DEG, thus we present the charge current  $J_c$  as a function  $t_{so}$  in Fig. 3(a). The induced  $J_c$  oscillates with RSOC constant, which comes from the Rashba spin precession since the oscillating period decreases with increase of the system size. When a spin-up or spin-down electron travels along the longitudinal direction in the RSOC region, the electronic wave function splits into two propagating waves with different wave vectors due to the RSOC, and at the collector the spin state of the electron depends on the interference between the two waves, and this is referred to as the Rashba spin precession, alternatively, it can be regarded as a spin precesses around the planar pseudomagnetic field from RSOC. The oscillation is also related to the Fermi energy of system due to multi-mode contributing to the current, at lower energy the oscillation period is comparatively larger because the smearing effect is weakened due to the less transverse modes involved at the Fermi energy. As is also shown in Fig. 3(a), the charge current  $J_c$  can be reversed as the RSOC strength varies, which is consistent

with the SHE in a finite size system<sup>[25]</sup> where the SHE can also reverse its direction with either RSOC constant or the system size. This characteristic may be helpful for experimental measurement of ISHE. The oscillation in Fig. 3(a) indicates that in the ISHE the charge current would oscillate with the sample size  $L$ , as is shown in Fig. 3(b), since the precession phase comes from the product of the length



**Fig. 3** (a) The charge current  $J_c$  as a function of the RSOC constant  $t_{so}$  for different longitudinal length  $L$  of the center sample with  $L = 10a, 20a, 30a$ . (b) The charge current  $J_c$  versus the longitudinal length  $L$  of the center sample for different spin-orbit coupled strength  $t_{so} = 0.02t, 0.04t$ . The other parameters  $\theta = \varphi = 0, E_f = 0.4t$ .

Figure 4 shows the transverse charge current  $J_c$  induced by the longitudinal pure spin current as a function of its spin polarization direction  $\theta$ , the azimuthal angle  $\varphi$  in 2DEG plane can not affect the charge current as can be seen from Eq. (12) where  $\varphi$  is absent. The optimal polarization angle of the spin bias is  $\theta = 0$  or  $\theta = \pi$ , which indicates that only the longitudinal  $\sigma_Z$  spin current can induce the transverse charge current (ISHE), and it is exactly reciprocal to the SHE effect.



**Fig. 4** The charge current  $J_c$  versus the angle  $\theta$  for different coupling strength  $\Gamma$  of the leads and the center scattering region with  $\Gamma = \Gamma_L = \Gamma_R = 0.05t, 0.08t, 0.1t$ . The other parameters are  $L = 30a, t_{so} = 0.1t, \varphi = 0, E_f = 0.4t$ .

At  $\theta = \pi/2$  or  $\theta = 3\pi/2$ , the spin polarization of spin bias at 2DEG plane can not lead to ISHE. This property is independent on other system parameters such as the line

$L$  and the RSOC constant. Similarly, at some lengths of sample the charge current direction can be reversed. The tendency of curves show that ISHE will smear as the sample size increases greatly. This corresponds to the agreement that the SHE or ISHE should survive in a finite size system and disappear in a infinite 2D system with linear  $k$ -dependent SOC.<sup>[10–11]</sup>

width function  $\Gamma$ , which can only influence the magnitude of the induced charge current and the whole profile of the  $J_c$  dependence on  $\theta$  keeps unchanged.

The ISHE discussed above can be used to detect the pure spin current since the detection of spin current is presently a challenge due to no direct method of measurement. The ISHE can not only give an indirect estimation of the magnitude of the pure spin current, but more importantly, it can give the spin polarization of pure spin current. It is noted that the measurement of the induced charge current in this Rashba system, should be performed in a mesoscopic system since the SHE and ISHE is not expected to exist in the macroscopic system due to the disorder scattering.

## 4 Conclusions

In summary, we have investigated the ISHE in a two-terminal nanosize device with RSOC in the scattering region. Based on a two lattice point model and Keldysh green's function, an analytic result of the induced transverse charge current can be derived and it fulfills the well-known relation  $\mathbf{J}_c \propto \mathbf{J}_s \times \mathbf{s}$ . It is found in a larger system that the charge current is dependent on the system parameters such as Fermi energy  $E_f$ , the RSOC strength  $t_{so}$ , and the direction of spin polarization of spin bias. The characteristic of the induced charge current likes its symmetric behavior with respect to the Fermi energy and the oscillation with respect to the RSOC strength are also revealed. These properties may help to exploit the ISHE in experiment.

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