Vol 16 No 6, June 2007
1009-1963/2007/16(06)/1748-05
Chinese Physics
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Electron transport for a laser-irradiated quantum channel with Rashba spin–orbit coupling*

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(Received 27 September 2006; revised manuscript received 21 November 2006)

We investigate theoretically the electron transport for a two-level quantum channel (wire) with Rashba spin–orbit coupling under the irradiation of a longitudinally-polarized external laser field at low temperatures. Using the method of equation of motion for Keldysh nonequilibrium Green function, we examine the time-averaged spin polarized conductance for the system with photon polarization parallel to the wire direction. By analytical analysis and a few numerical examples, the interplay effects of the external laser field and the Rashba spin–orbit coupling on the spin-polarized conductance for the system are demonstrated and discussed. It is found that the longitudinally-polarized laser field can adjust the spin polarization rate and produce some photon sideband resonances of the conductance for the system.

Keywords: Rashba quantum wire, laser field, spin-polarized transport, nonequilibrium Green function
PACC: 7320D, 7335, 7865K

Recently, much attention has been paid to the manipulation of the electron spin degree of freedom for applications in spintronics.[1,2] There have been several suggestions to use the electron spin–orbit coupling (SOC) in semiconductor mesoscopic systems to accumulate the spin polarization by applying an external field.[3,4] And many fundamental and interesting phenomena have been revealed for these systems.[5−7] In a two-dimensional electron gas (2DEG) based on semiconductor heterojunction, two types of SOCs are usually taken into account, namely Rashba[8] and Dresselhaus[9] types.

On the other hand, there also exists a great amount of work on time-dependent mesoscopic transport.[10] The electron transport for a quantum channel (quantum wire) without SOC in the presence of a time-varying electromagnetic (EM) field has been analysed by means of the nonequilibrium Green function (NGF)[11] and scattering matrix approach,[12] separately. However, the transport property for a mesoscopic system in the presence of both the SOC and an EM electric field has become an interesting topic recently.[13] Therefore, we have been motivated to investigate theoretically the interplay effect between the Rashba SOC and a transversely-polarized laser field on the transport for a quantum wire by means of NGF.[14] In this work we further study the electron transport for a Rashba quantum wire irradiated by a longitudinally-polarized external laser field. Also using the NGF, we demonstrate the different effects between the transversely- and longitudinally-polarized laser fields on the conductance for the system.

The NGF approach has been employed in last decades to study a variety of problems beyond the linear response regime.[15] We will use this approach to standard nonequilibrium Keldysh equation of motion (EOM) in the present work. We consider a quasi-one-dimensional system of electrons in the presence of Rashba SOC and a longitudinally-polarized laser field. In this case the Hamiltonian of the system reads

$$H = \frac{\boldsymbol{p}^2}{2m^*} + V(\boldsymbol{r}) + H_R + V(t), \tag{1}$$

where $\boldsymbol{r} = (x, y)$ and $\boldsymbol{p} = (p_x, p_y)$ are two-dimensional position and momentum vectors respectively and m^* is the effective mass of the electrons in the semiconductor heterojunction. The electrons are confined in the y-direction by an infinite square-well potential of width a. The Rashba SOC Hamiltonian is generally in

*Project supported by the National Natural Science Foundation of China (Grant No 10574042), and the Hunan Provincial Natural Science Foundation of China (Grant No 06JJ2097).
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the form of $H_R = \frac{\hbar k_R}{m^*}(\sigma_x p_y - \sigma_y p_x)$ with the characteristic wavevector k_R, and $V(t)$ is the potential from the interaction between the external time-dependent laser field and the electrons in the system.

In order to write the Hamiltonian in the second-quantized form, we define that $a^+_{ks\alpha}(a_{ks\alpha})$ creates (annihilates) an electron with wavevector k and spin s ($s = \uparrow/\downarrow$ or $+1/\text{-}1$ is the spin branch index corresponding to spin-up/-down) in either the left (L) or the right (R) lead, and $c^+_{k_x ns}(c_{k_x ns})$ creates (annihilates) an electron in the nth transverse mode $|k_x, n, s\rangle$ with wavevector k_x and a spin s in the absence of SOC in the quantum wire modelled as a two-level ($n = 1, 2$) system. In terms of the above operators, the Hamiltonian (1) becomes

$$\begin{aligned} H = & \sum_{k,s,\alpha\in L/R} \varepsilon_{ks\alpha} a^+_{ks\alpha} a_{ks\alpha} + \sum_{k_x,n,s} \varepsilon_{ns}(k_x) c^+_{k_x ns} c_{k_x ns} + \sum_{k,k_x,n,s,\alpha\in L/R} (T^\alpha_{kk_x ns} a^+_{ks\alpha} c_{k_x ns} + \text{h.c.}) \\ & + \sum_{k_x,n,n',s,s'} [\gamma_{nn'}\beta_{ss'} + V_{nsn's'}\cos(\Omega t)] c^+_{k_x ns} c_{k_x n's'}, \end{aligned} \tag{2}$$

where $\varepsilon_{ks\alpha}$ is the energy level in lead α, and

$$\varepsilon_{ns}(k_x) = \frac{\hbar^2}{2m^*}\left[(k - sk_R)^2 + \left(\frac{n\pi}{a}\right)^2\right] - \Delta_R \tag{3}$$

is the nth sublevel in the wire with $\Delta_R = \hbar^2 k_R^2/(2m^*)$. In Hamiltonian (2), the coupling between the electrode leads and the wire with strength $T^\alpha_{kk_x ns}$ is represented by the third term, and the last term describes both the adiabatical electron-photon interaction between the wire and the mixture of transverse modes due to the SOC, where $V_{nsn's'}$ are the dipole electron-photon interaction[11] matrix elements (MEs) and Ω is the incident laser frequency. Since the frequencies of interest are in the range corresponding to wavelengths of the order of hundreds of nanometres, the spatial variation of the field potential can be neglected. The Rashba SOC mixes the transverse modes through ME $\gamma_{nn'}\beta_{ss'}$, where

$$\gamma_{nn'} = \frac{4nn'}{a(n^2 - n^2)}(-1)^{\frac{n+n'-1}{2}}(1 - \delta_{nn'}), \tag{4}$$

and $\beta_{ss'}$ is the element of matrix

$$\beta = \frac{\hbar^2 k_R}{m^*}\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \tag{5}$$

according to the confining potential. For the system with only Rashba SOC, the spin-polarization axis is along the SOC induced effective magnetic field[15] for waves propagating in the x-direction, then we have a spin state

$$|s\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} s(i+1) \\ i-1 \end{pmatrix}. \tag{6}$$

It is the linear combination of the two eigenstates of σ_z, with equal probability occupying the real spin-up and -down states respectively in the original spin space.[14] Moreover, in the above Hamiltonian we have neglected the electron-electron interaction since its effect can be plausibly taken into a renormalized SOC constant.[16]

Further, according to the Dyson equation, the coupling between the electrode leads and the wire only adds a self-energy in the NGF, so we firstly calculate the Green's Function (GF) of the quantum wire without considering the electrode leads. In this case the Hamiltonian of the quantum wire part in the absence of laser field reads

$$\begin{aligned} H_{\text{wire}} = & \sum_{k_x}[\varepsilon_{1\uparrow}(k_x) c^+_{k_x 1\uparrow} c_{k_x 1\uparrow} + \varepsilon_{1\downarrow}(k_x) c^+_{k_x 1\downarrow} c_{k_x 1\downarrow} \\ & + \varepsilon_{2\uparrow}(k_x) c^+_{k_x 2\uparrow} c_{k_x 2\uparrow} + \varepsilon_{2\downarrow}(k_x) c^+_{k_x 2\downarrow} c_{k_x 2\downarrow} \\ & + \varepsilon_R(c^+_{k_x 2\uparrow} c_{k_x 1\downarrow} + c^+_{k_x 1\downarrow} c_{k_x 2\uparrow} - c^+_{k_x 1\uparrow} c_{k_x 2\downarrow} \\ & - c^+_{k_x 2\downarrow} c_{k_x 1\uparrow})], \end{aligned} \tag{7}$$

where $\varepsilon_R = 8\hbar^2 k_R/(3m^* a)$, and the spin-up and -down states are determined by Eq.(6).

For definiteness,[14] we consider the case where the applied incident laser is longitudinally-polarized along the x-direction (parallel to the wire), hence the off-diagonal electron-photon interaction MEs are simply zero in the dipole approximation.[11,14] Also for simplicity in calculation we assume phenomenologically that the diagonal electron-photon interaction MEs $V_{1s1s'} = V_{2s2s'} = 1.0$ as the free input parameters (dependent on incident laser intensity).[14] Thus the Hamiltonian of the wire part in the presence of laser field becomes

$$
\begin{aligned}
H'_{wire} = \sum_{k_x} \Big\{ & \Big[\varepsilon_{1\uparrow}(k_x) + \frac{1}{2}(\mathrm{e}^{\mathrm{i}\Omega t} + \mathrm{e}^{-\mathrm{i}\Omega t})\Big] c^+_{k_x 1\uparrow} c_{k_x 1\uparrow} + \Big[\varepsilon_{1\downarrow}(k_x) + \frac{1}{2}(\mathrm{e}^{\mathrm{i}\Omega t} + \mathrm{e}^{-\mathrm{i}\Omega t})\Big] c^+_{k_x 1\downarrow} c_{k_x 1\downarrow} \\
& + \Big[\varepsilon_{2\uparrow}(k_x) + \frac{1}{2}(\mathrm{e}^{\mathrm{i}\Omega t} + \mathrm{e}^{-\mathrm{i}\Omega t})\Big] c^+_{k_x 2\uparrow} c_{k_x 2\uparrow} + \Big[\varepsilon_{2\downarrow}(k_x) + \frac{1}{2}(\mathrm{e}^{\mathrm{i}\Omega t} + \mathrm{e}^{-\mathrm{i}\Omega t})\Big] c^+_{k_x 2\downarrow} c_{k_x 2\downarrow} \\
& + \frac{1}{2}(\mathrm{e}^{\mathrm{i}\Omega t} + \mathrm{e}^{-\mathrm{i}\Omega t})(c^+_{k_x 1\uparrow} c_{k_x 1\downarrow} + c^+_{k_x 1\downarrow} c_{k_x 1\uparrow} + c^+_{k_x 2\uparrow} c_{k_x 2\downarrow} + c^+_{k_x 2\downarrow} c_{k_x 2\uparrow}) + \varepsilon_R (c^+_{k_x 2\uparrow} c_{k_x 1\downarrow} \\
& + c^+_{k_x 1\downarrow} c_{k_x 2\uparrow} - c^+_{k_x 1\uparrow} c_{k_x 2\downarrow} - c^+_{k_x 2\downarrow} c_{k_x 1\uparrow}) \Big\}, \qquad (8)
\end{aligned}
$$

which is similar to Eq.(12) in Ref.[14] with a different structure.

Next, we employ the usually defined retarded GF[11,14,17]

$$
\begin{aligned}
& G^r_{nsn's'}(t_2, t_1) \\
= & \ll c_{k_x ns}(t_2), c_{k_x n's'}(t_1) \gg^r \\
= & -\mathrm{i}\theta(t_2 - t_1)\langle\{c_{k_x ns}(t_2), c_{k_x n's'}(t_1)\}\rangle, \qquad (9)
\end{aligned}
$$

then its corresponding Keldysh EOM is

$$
\begin{aligned}
& \mathrm{i}\frac{\partial}{\partial t_2} \ll c_{k_x ns}(t_2), c_{k_x n's'}(t_1) \gg^r \\
= & \ \delta(t_2 - t_1)\langle\{c_{k_x ns}(t_2), c_{k_x n's'}(t_1)\}\rangle \\
& + \ll [c_{k_x ns}(t_2), H], c_{k_x n's'}(t_1) \gg^r . \qquad (10)
\end{aligned}
$$

Inserting Hamiltonian (8) into Eq.(10) and transforming the variables to $t_2 - t_1$ and t_1, and then performing the Fourier transform to change the variable $t_2 - t_1$ to ω, we finally obtain the diagonal MEs of the two retarded GFs without the coupling between the electrode leads and wire

$$
\{[\omega - \varepsilon_{1/2\uparrow}(k_x)][\omega - \varepsilon_{2/1\downarrow}(k_x)] - \varepsilon_R^2\} \ll c_{k_x 1/2\uparrow}, c^+_{k_x 1/2\uparrow} \gg^r_\omega = \omega - \varepsilon_{2/1\downarrow}(k_x), \qquad (11)
$$

$$
\{[\omega - \varepsilon_{1/2\downarrow}(k_x)][\omega - \varepsilon_{2/1\uparrow}(k_x)] - \varepsilon_R^2\} \ll c_{k_x 1/2\downarrow}, c^+_{k_x 1/2\downarrow} \gg^r_\omega = \omega - \varepsilon_{2/1\uparrow}(k_x), \qquad (12)
$$

$$
\begin{aligned}
& [\omega - \varepsilon_{1/2\uparrow}(k_x)] \ll c_{k_x 1/2\uparrow}, c^+_{k_x 1/2\uparrow}(t_1) \gg^r_\omega \\
= & \ 1 \mp \varepsilon_R \ll c_{k_x 2/1\downarrow}, c^+_{k_x 1/2\uparrow}(t_1) \gg^r_\omega + \frac{1}{2}\mathrm{e}^{\mathrm{i}\Omega t_1}[\ll c_{k_x 1/2\uparrow}, c^+_{k_x 1/2\uparrow}(t_1) \gg^r_{\omega+\Omega} \\
& + \ll c_{k_x 1/2\downarrow}, c^+_{k_x 1/2\uparrow}(t_1) \gg^r_{\omega+\Omega}] + \frac{1}{2}\mathrm{e}^{-\mathrm{i}\Omega t_1}[\ll c_{k_x 1/2\uparrow}, c^+_{k_x 1/2\uparrow}(t_1) \gg^r_{\omega-\Omega} \\
& + \ll c_{k_x 1/2\downarrow}, c^+_{k_x 1/2\uparrow}(t_1) \gg^r_{\omega-\Omega}], \qquad (13)
\end{aligned}
$$

$$
\begin{aligned}
& [\omega - \varepsilon_{1/2\downarrow}(k_x)] \ll c_{k_x 1/2\downarrow}, c^+_{k_x 1/2\downarrow}(t_1) \gg^r_\omega \\
= & \ 1 \pm \varepsilon_R \ll c_{k_x 2/1\uparrow}, c^+_{k_x 1/2\downarrow}(t_1) \gg^r_\omega + \frac{1}{2}\mathrm{e}^{\mathrm{i}\Omega t_1}[\ll c_{k_x 1/2\downarrow}, c^+_{k_x 1/2\downarrow}(t_1) \gg^r_{\omega+\Omega} \\
& + \ll c_{k_x 1/2\uparrow}, c^+_{k_x 1/2\downarrow}(t_1) \gg^r_{\omega+\Omega}] + \frac{1}{2}\mathrm{e}^{-\mathrm{i}\Omega t_1}[\ll c_{k_x 1/2\downarrow}, c^+_{k_x 1/2\downarrow}(t_1) \gg^r_{\omega-\Omega} \\
& + \ll c_{k_x 1/2\uparrow}, c^+_{k_x 1/2\downarrow}(t_1) \gg^r_{\omega-\Omega}], \qquad (14)
\end{aligned}
$$

for spin-up and -down electrons, respectively. It is seen from Eqs.(13) and (14) that G^r_0 with frequency ω is coupled to the components with photon sidebands frequencies of $\omega + \Omega$ and $\omega - \Omega$ through Rashba SOC characteristic wavevector k_R.

On the other hand, the self-energy describing the influence of the leads can be simply written as

$$
\begin{aligned}
\Sigma_{nn'} \equiv & \ \Sigma^{L/R}_{nn'}(\omega) \\
= & \ 2\pi \sum_{k,k_x,s} (T^\alpha_{kk_x ns})^* T^\alpha_{kk_x n's'} \delta(\omega - \varepsilon_{ks\alpha}), \qquad (15)
\end{aligned}
$$

with which one can construct the GF of $G^r = [(G_0)^{-1} - \mathrm{i}\Sigma]^{-1}$ for the whole system. If we calculate the time-averaged GF up to the second order, then at

low temperatures the conductance of the system has the form of Landauer-type[11,18]

$$G = \frac{e^2}{h}\mathrm{Tr}[\Sigma^{\mathrm{L}}(\omega)G^a(\omega,\omega)\Sigma^{\mathrm{R}}G^r(\omega,\omega)], \qquad (16)$$

where the $G^r(\omega,\omega)$ and $G^a(\omega,\omega)$ represent the time-averaged retarded and advanced GF, respectively.

In the following, we numerically solve the set of coupled linear equations (11)–(14) including all components with frequencies from $\omega \pm \Omega$ to $\omega \pm 3\Omega$ and present a few numerical examples of the conductance for the system according to Eq.(16). In our numerical calculation, the physical quantities are chosen to be those in an InAs semiconductor heterostructure[14,19] of effective mass $m^* = 0.036\, m_{\mathrm{e}}$ and Rashba SOC constant $\alpha = 4.5 \times 10^{-11}\,\mathrm{eVm}$, thus yielding the SOC characteristic wavevecter $k_{\mathrm{R}} = m^*\alpha/\hbar^2 = 2.1 \times 10^7\,\mathrm{m}^{-1}$ and energy $\Delta_R = \hbar^2 k_{\mathrm{R}}^2/(2m^*) = 0.5\,\mathrm{meV}$. We have selected hard-wall transverse confining potential with width $a = 100\,\mathrm{nm}$ and the energy unit $E^* = \epsilon_1 = \pi^2\hbar^2/(2m^*a^2) = 1.0\,\mathrm{meV}$ (i.e. the first lateral level of the quantum wire without SOC), hence the corresponding time unit $t^* = \hbar/E^* = 6.3\times10^{-13}\,\mathrm{s}$ and the frequency unit $\Omega^* = 1/t^* = 1.6\,\mathrm{THz}$. With these units, the propagating longitudinal wavevector corresponding to the nth transverse mode is $k_x = (\omega - n^2)^{1/2}$. In the wide-band approximation the real part of the self-energy in negligible,[11,17,18] and we simply assume that $\Sigma_{11} = \Sigma_{22} = 0.10$ and $\Sigma_{12} = \Sigma_{21} = 0.05$. The choice of these typical parameters is based on the following consideration.[11,14] Usually the strength of electron-photon interaction depends on the photon intensity, polarization and size of the quantum wire. Under the irradiation of a strong laser with an electric field of the order $10^5 - 10^6\,\mathrm{V/m}$, the MEs are comparable with or several times larger than the level spacing in quantum wire with the width of $10 - 100\,\mathrm{nm}$ (corresponding to the external laser frequency $\sim$THz), and these quantities are physically realizable in recent experiment.[20]

Firstly, the conductance (in units of e^2/h) as a function of energy ($\sim \omega$, in units of ϵ_1) in the absence of laser field with Rashba SOC for the system is illustrated in Fig.1(a), where the solid (dashed) line is for spin-up (-down) electrons. It is commonly known that the electron energy spectrum is degenerate for the two spin orientations in the absence of SOC. In the presence of SOC the energy spectrum (3) satisfies the condition $\varepsilon_{n,s}(k_x) = \varepsilon_{n,-s}(-k_x)$ in accordance with the time inversion symmetry. As a consequence of the two-subband level structure of the wire, there are two major peaks (corresponding to the two levels like quantum dot) in the conductance curves because of the finite coupling between the leads and the wire. Owing to the SOC the conductances for the two spin orientation are different in peak height and shape, but the peak positions are not changed because the SOC-split energy is much less than the level spacing of the wire ($\Delta_R \ll \epsilon_2 - \epsilon_1$).

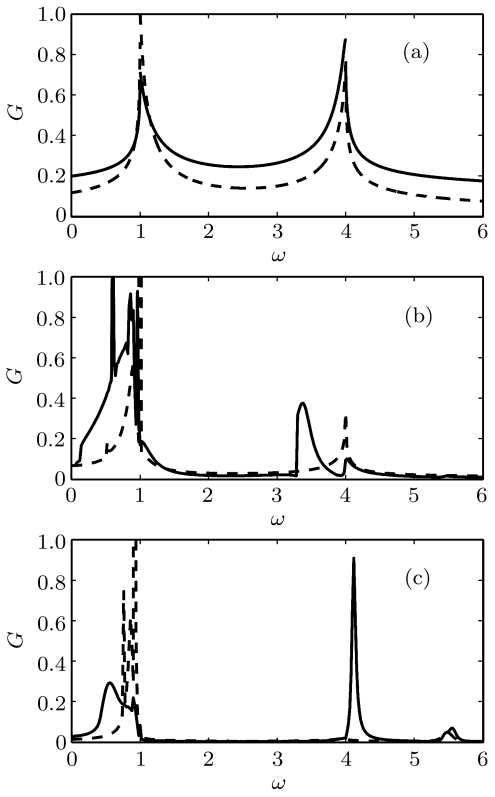


Fig.1. The plotted conductance (in units of e^2/h) as a function of energy ($\sim \omega$, in units of ϵ_1) (a) in the absence of laser field with Rashba wavevector $k_R = 1/(2\pi)$, (b) in the presence of laser field of frequency Ω= 0.8 THz with $k_R = 1/(2\pi)$ and (c) in the presence of laser field of frequency Ω= 0.8 THz with $k_R = 1/\pi$ where the solid (dashed) line for the spin-up (-down) electrons (in (a) the solid is shift 0.1 upward for clarity).

However, our interest is the interplay effect of the external laser field and the Rashba SOC on the electron transport for the system. The time-averaged conductance of the system irradiated by a longitudinally-polarized laser field in the presence of Rashba SOC is shown in Fig.1(b) with field frequency $\Omega = 0.5$ units =0.8 THz and $k_{\mathrm{R}} = 1/(2\pi)$. We can see clearly that the conductance for spin-up electrons has some photon sideband peaks at $\omega = 0.5$, 0.8, 3.3. On the other hand, comparing with Fig.1(a) the conductance for spin-down electrons is almost not changed

in this case except that the second main peak is suppressed. In addition, the backgrounds (excluding both the main peaks and the sideband peaks) of the spin-polarized conductances are suppressed to nearly zero in the range of $\omega > 1$. However, when the Rashba SOC strength increases twice ($k_{\rm R} = 1/\pi$) as shown in Fig.1(c), the conductances for both the spin-up and -down electrons show some photon sideband peaks around the two main peaks due to the stronger SOC strength. And the backgrounds of the spin-polarized conductances are more suppressed in this case. Comparing the results here with that of the same system under transversely-polarized laser field irradiation,[14] we conclude that the externally applied laser field with transversal and longitudinal polarizations to the wire can be used to adjust the spin-polarized conductance and the polarization rate for the system. However, because of the different physical mechanisms, the height and the position of the conductance peaks are different for the types of field polarizations, which can be clearly observed from the numerical examples with the same system parameters and the incident frequency.

In conclusion, we have theoretically investigated the electronic transport property of a two-sublevel quantum wire irradiated by a longitudinally-polarized external laser field in the presence of Rashba SOC. The time-averaged conductances for spin-up and spin-down electrons are calculated analytically and demonstrated numerically. It is found that the external laser field can change the spin-polarized conductance for the system. However, the experimental observation for this proposal and further theoretical investigation, with the impurity, phonon or electron-electron interaction taken into account, are worth carrying out.

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