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# Spin polarization direction switch based on an asymmetrical quantum wire

Zhonghui Xu [a,b], Xianbo Xiao [c], Yuguang Chen [a,*]

[a] Department of Physics, Tongji University, Shanghai 200092, China
[b] Faculty of Information Engineering, Jiangxi University of Science and Technology, Ganzhou 341000, China
[c] School of Computer, Jiangxi University of Traditional Chinese Medicine, Nanchang 330004, China

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ABSTRACT

A scheme for a spin polarization direction switch is investigated by studying the spin-dependent electron transport of an asymmetrical quantum wire with Rashba spin–orbit coupling. It is found that the spin polarization direction can be switched by changing the direction of the external current. The physical mechanism of this device arises from the fact that the symmetries in the longitudinal and transverse directions are all broken but $C_2$-rotation and time-reversal symmetries are still preserved. Further studies show that the spin polarization is robust against disorder, displaying the feasibility of the proposed structure for a potential application.



## 1. Introduction

In the past decades, spin-dependent electron transport in low-dimensional mesoscopic systems has been investigated extensively both for fundamental physics and for potential applications in spintronic devices [1–3], in which the electron spin degree of freedom may be used as well as its charge for information processing. The basis of this application is the generation of spin-polarized current and quantum control of coherent spin states. The Rashba spin–orbit coupling (SOC) [4] plays an important role in spin-dependent electron transport, since Rashba SOC strength can be tuned by external gate voltage conveniently [5–7].

By Rashba SOC in semiconductors nanostructures, several spin filtering devices have been proposed, such as T-shape electron waveguide [8–12], quantum wires [13–17], two-dimensional electron gas (2DEG) [18,19], ballistic Rashba bar [20], one-dimensional gated superlattice [21], and quantum rings [22]. Recently, Zhai et al. have proposed a spin current diode based on a hornlike electron waveguide with Rashba SOC and found that a quite different magnitude of spin-polarized current can be achieved when the transport direction is reversed [23]. The physical mechanism of the proposed device arises from spin-flipped transitions caused by the spin–orbit interaction. However, only transversal spin conductance could be nonvanishing in the considered system. This phenomenon may be due to that its mirror symmetry along the transverse direction is broken and the symmetry along the longitudinal direction is remained. The spin-polarized transport properties of a Rashba step-like quantum wire were also investigated [24]. And a very large spin conductance can be obtained when the forward bias is applied to the structure, while the conductance may be suppressed when the transport direction is reversed. This effect is owing to the different local density of electron states (LDOS) in the quantum wire when the transport direction is reversed. In this system, the two types of mirror symmetries (along the longitudinal and the transverse directions) of the step-like quantum wire are all destroyed, and the $C_2$-rotation symmetry [25] will also be invalid. Thus it is not clear what will happen when the two types of mirror symmetries of the investigated system are all destroyed, but the $C_2$-rotation symmetry is preserved.

Inspired by the above mentioned works, in this Letter, we study the spin-dependent electron transport for an asymmetrical quantum wire (QW), in which transversal and longitudinal symmetries are all broken, however, the $C_2$-rotation symmetry is still preserved. The spin-polarized current is calculated by the recursive Green's function method [26] for the backward and forward biased cases. Furthermore, disorder is introduced into our system. Its effects on the spin-polarized current are also studied. The organization of this Letter is as follows. In Section 2, the theoretical model and the calculation method are presented. In Section 3, the numerical results are illustrated and discussed. Conclusions are given in Section 4.

* Corresponding author. Tel./fax: +86 021 65986350.
*E-mail address:* ygchen@tongji.edu.cn (Y. Chen).

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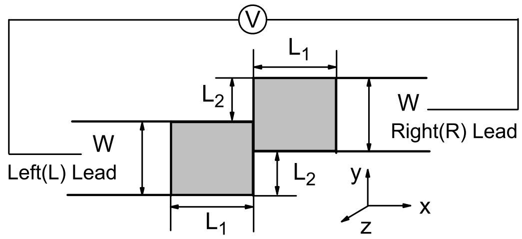


**Fig. 1.** Schematic diagram of the asymmetrical QW with Rashba SOC. The left and right regions of the asymmetrical QW have the same length $L_1$ and uniform width $W$. The measure of the spatial shift of two regions which for the quantum wire is $L_2$.

## 2. Model and analysis

Our system is illustrated in Fig. 1, where a 2DEG in the $(x, y)$ plane is restricted to an asymmetrical QW by a confining potential $V(x, y)$. The SOC arises dominantly from the Rashba mechanism since the 2DEG is confined in an asymmetric quantum well. The asymmetrical QW consists of two regions, the left and right regions, having equal length $L_1$ and uniform width $W$. The two connecting leads are normal-conductor electrodes without SOC, since we are only interested in spin-unpolarized injection. Using the spin-resolved discrete lattice model, the tight-binding Hamiltonian including the Rashba SOC on a square lattice is given as follows [27,28],

$$\begin{aligned} H = {} & \sum_{l,m,\sigma} \varepsilon_{l,m,\sigma} C^{\dagger}_{l,m,\sigma} C_{l,m,\sigma} - t \sum_{l,m,\sigma} \{ C^{\dagger}_{l+1,m,\sigma} C_{lm\sigma} \\ & + C^{\dagger}_{l,m+1,\sigma} C_{l,m,\sigma} + \text{H.c.} \} \\ & + t_{so} \sum_{l,m,\sigma\sigma'} \{ C^{\dagger}_{l+1,m,\sigma'} (i\sigma_y)_{\sigma\sigma'} C_{l,m,\sigma} \\ & - C^{\dagger}_{lm+1\sigma'} (i\sigma_x)_{\sigma\sigma'} C_{l,m,\sigma} + \text{H.c.} \} \\ & + \sum_{l,m,\sigma} V_{l,m} C^{\dagger}_{l,m,\sigma} C_{l,m,\sigma}, \end{aligned} \tag{1}$$

where $C^{\dagger}_{l,m,\sigma}$ $(C_{l,m,\sigma})$ is the creation (annihilation) operator of electron at site $(l, m)$ with spin $\sigma$ $(\sigma = \uparrow, \downarrow)$, $\sigma_x$ and $\sigma_y$ are Pauli matrices. The on-site energy $\varepsilon_{l,m,\sigma} = 4t$ with the hopping energy $t = \hbar^2/2m^*a^2$, where $m^*$ is the effective mass of the electrons and $a$ is the lattice constant. The Rashba SOC is $t_{so} = \alpha/2a$ with the Rashba constant $\alpha$, and $V_{l,m}$ is an additional confining potential. The Anderson disorder can be introduced by the fluctuation of the on-site energies, which distributes randomly within the range width $w$ $[V_{l,m} \to V_{l,m} + w_{l,m}$ with $-w/2 < w_{l,m} < w/2]$ [29–33].

Utilizing the recursive Green's function method [26], the spin-dependent conductance from arbitrary lead $p$ to lead $q$ is given by [27],

$$G^{\sigma'\sigma} = e^2/hTr\left[\Gamma^{\sigma}_p G^r \Gamma^{\sigma'}_q G^a\right], \tag{2}$$

where $\Gamma_{p(q)} = i[\sum^r_{p(q)} - \sum^a_{p(q)}]$ with the self-energy from the lead $\sum^r_{p(q)} = (\sum^a_{p(q)})^*$, the trace is over the spatial and spin degrees of freedom. $G^r$ $(G^a)$ is the retarded (advanced) Green function of the whole system and $G^a = (G^r)^{\dagger}$. The LDOS is described as [34],

$$\rho(\vec{r}, E) = -\frac{1}{2\pi} A(\vec{r}, E) = -\frac{1}{\pi} Im\left[G^r(\vec{r}, E)\right], \tag{3}$$

in which $A \equiv i[G^r - G^a]$ is the spectral function, and $E$ is the electron energy.

In our calculations, the structural parameters of the asymmetrical QW are fixed at $L_1 = 10a$, $W = 10a$, and $L_2 = 6a$. The electron effective mass is taken to be $0.067m_0$, $m_0$ is the free electron mass, which is appropriate to a $GaAs/Al_xGa_{1-x}As$ quantum well system [35]. All energies are normalized by the hopping energy $t$. The $z$-axis is chosen as the spin quantization axis, so $|\uparrow\rangle = (1, 0)^T$ represents the spin-up state and $|\downarrow\rangle = (0, 1)^T$ denotes the spin-down state. The boundary of the QW is determined by the hard-well confining potential. The total charge conductance and spin polarization of $z$-component are defined as $G^e = G^{\uparrow\uparrow} + G^{\downarrow\uparrow} + G^{\downarrow\downarrow} + G^{\uparrow\downarrow}$ and $P_z = [(G^{\uparrow\uparrow} + G^{\uparrow\downarrow}) - (G^{\downarrow\downarrow} + G^{\downarrow\uparrow})]/G^e$, respectively.

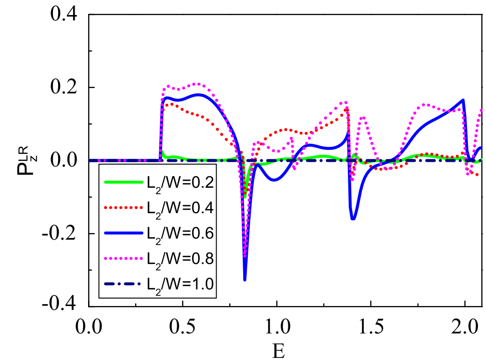


**Fig. 2.** (Color online.) The spin polarization as a function of the electron energy in the forward biased case for different $L_2/W$. The Rashba SOC strength $t_{so} = 0.177$.

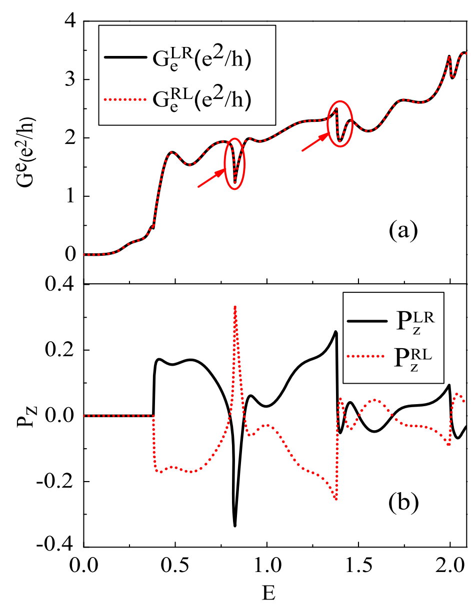


**Fig. 3.** (Color online.) (a) The charge conductance of an asymmetrical QW as a function of the electron energy for spin-unpolarized electron injections (black curve is for the left–right moving electrons and red curve is for the right–left moving electrons). (b) The corresponding spin conductance from lead L to R (the black curve) and lead R to L (the red curve). The Rashba SOC strength $t_{so} = 0.177$.

## 3. Results and discussion

To ensure the dependence of the results for the spin-resolved conductance and the out-of-plane spin polarization on this asymmetry parameter measured, we have calculated the spin polarization as a function of the electron energy in the forward biased case for different $L_2/W$. As shown in Fig. 2, it is a large spin polarization with $L_2/W = 0.6$, in our calculations, the width of the asymmetrical QW $W = 10a$, thus, the measure of the spatial shift of two regions which for the quantum wire is $L_2 = 6a$.

In Fig. 3, we show the total charge conductance and corresponding spin polarization as a function of the electron energy.