A scheme for a spin polarization direction switch is investigated by studying the spin-dependent electron transport of an asymmetrical quantum wire (QW) with Rashba spin-orbit coupling (SOC).

It is found that the magnitude of the spin-polarized current in the backward biased case is equal to it in the forward biased case but their signs are contrary. This results indicate that the spin polarization direction can be switched by changing the direction of the external current. The physical mechanism of this device may arise from the symmetries in the longitudinal and transverse directions are broken but $C_2$-rotation and time-reversal symmetries are still reserved. Further studies show that the spin polarization is robust against disorder, displaying the feasibility of the proposed structure for a potential application.
In the past decades, spin-dependent electronic transport in low-dimensional mesoscopic systems has been investigated extensively both for fundamental physics and for potential applications in spintronic devices\(^1\), 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 SOC\(^2\) plays an important role in spin-dependent electronic transport. SOC can be used to manipulate spin states and its strength can be tuned by external gate voltage conveniently\(^3\)\(^−\)\(^5\).

By introducing Rashba SOC in semiconductors nanostructures, several spin filtering devices have been proposed without need for a magnetic element or an external magnetic field, such as T-shape electron waveguide\(^6\)\(^−\)\(^10\), quantum wires\(^11\)\(^−\)\(^14\), two-dimensional electron gas (2DEG)\(^15\), and quantum rings\(^16\). 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\(^17\). 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, due to its mirror symmetry along the transverse direction is broken but respect to the longitudinal direction is remained. The spin-polarized transport properties of a Rashba step-like quantum wire is also investigated by Xiao and Chen\(^18\). It is shown that a very large spin conductance can be obtained when the forward bias is applied to the structure, while it is vanished or suppressed when the transport direction is reversed. This effect is owing to the different local density of electron states in the quantum wire when the transport direction is reversed. However, the two types mirror symmetries (longitudinal and transverse direction symmetries) of the step-like quantum wire are all destroyed, and the \(C_2\) rotation symmetry\(^19\) will also be invalid. Thus it is not known whether a large spin-polarized current could be generated when the two types mirror symmetries of the investigated system are all destroyed, but the \(C_2\) rotation symmetry is remained. Further, the influence of the disorder for a real application, remains unclear.

Inspired by the two works above, in this paper, we study the spin-dependent electron transport for an asymmetrical quantum wire, in which transversal and longitudinal symmetries are all broken, however, the \(C_2\) rotation symmetry is reserved. It is found that the magnitude of the spin-polarized current in the backward biased case is equal to it in the for-
ward biased case but their signs are contrary. This results indicate that the spin polarization direction can be switched by changing the direction of the external current. Furthermore, this spin-polarized current can survive even in the presence of strong disorder. Therefore, a spin polarization direction switch device can be devised by using this system.

The system investigated in present work is schematically depicted in Fig. 1, where a 2DEG in the \((x, y)\) plane is restricted to a an asymmetrical quantum wire by a transverse confining potential \(V(x, y)\). The SOC is assumed to arise dominantly from the Rashba mechanism since the 2DEG is confined in a asymmetric quantum well. The asymmetrical QW consists of two regions, the left and right regions have the same length \(L_1\) and a uniform width \(W_1\). The two connecting leads are normal-conductor electrodes without SOC since we are only interested in spin-unpolarized injection. We choose the coordinate system such that the \(x\) axis, with \(l\) lattice sites, is in the longitudinal direction, while the \(y\) axis, with \(m\) lattice sites, is in the transverse direction. To describe the electronic properties of the effective discretized system of square lattice, one can define the tight-binding Hamiltonian including the Rashba SOC on a square lattice as follows

\[
H = \sum_{lm\sigma} \varepsilon_{lm\sigma} C_{lm\sigma}^\dagger C_{lm\sigma} - t \sum_{lm\sigma} \{C_{l+1m\sigma}^\dagger C_{lm\sigma} + C_{lm+1\sigma}^\dagger C_{lm\sigma} + H.c\} + t_{so} \sum_{lm\sigma\sigma'} \{C_{l+1m\sigma'}^\dagger (i\sigma_y)_{\sigma\sigma'} C_{lm\sigma} - C_{lm+1\sigma'}^\dagger (i\sigma_x)_{\sigma\sigma'} C_{lm\sigma} + H.c\} + \sum_{lm\sigma} V_{lm} C_{lm\sigma}^\dagger C_{lm\sigma},
\]

in which \(C_{lm\sigma}^\dagger (C_{lm\sigma})\) is the creation (annihilation) operator of electron at site \((lm)\) with spin \(\sigma (\sigma = \uparrow, \downarrow)\), and \(\sigma_x\) and \(\sigma_y\) are Pauli matrix. The on-site energy \(\varepsilon_{lm\sigma} = 4t\) with the hopping energy \(t = \hbar^2/2m^*a^2\), here \(m^* = 0.067m_0\) is effective mass of electron and \(a\) is lattice constant. The Rashba SOC is \(t_{so} = \alpha/2a\) with the Rashba constant \(\alpha\). \(V_{lm}\) is the additional confining potential. The Anderson disorder can be introduced by the fluctuation of the on-site energies, which distributes randomly within the range width \(w\) \([\varepsilon_{lm\sigma} = \varepsilon_{lm\sigma} + w_{lm}\) with \(-w/2 < w_{lm} < w/2\)].

The spin-dependent conductance from arbitrary lead \(p\) to lead \(q\) is given by

\[
G^{\sigma\sigma'} = e^2/h Tr[\Gamma_N^{\sigma\sigma'} \Gamma_{W}^{\sigma\sigma'} G^{\sigma\sigma'}],
\]

where \(\Gamma_N^{\sigma\sigma'} = i[\sum_r^{N(W)} - \sum_a^{W(W)}]\) with the self-energy from the narrow (wide) lead \(\sum_r^{N(W)} = (\sum_a^{W(W)})^*\), the trace is over the spatial degrees of freedom, and \(G_r^{\sigma\sigma'}(G_a^{\sigma\sigma'})\) is
the retarded (advanced) Green function of the whole system that can be computed by the
spin-resolved recursive Green function method\textsuperscript{21}.

The local density of electron states (LDOS) is described as\textsuperscript{22}
\begin{equation}
\rho(\vec{r}, E) = -\frac{1}{2\pi} A(\vec{r}, E) = -\frac{1}{\pi} \text{Im}[G_r(\vec{r}, E)],
\end{equation}
where $A \equiv i[G_r - G_a]$ is the spectral function, and $E$ is the electron energy. In the
calculations, the asymmetrical QW is taken to be that in a 2DEG of high-mobility
$GaAs/Al_xGa_{1-x}As$ with a typical electron density $n \sim 2.5 \times 10^{11}$ /cm$^2$, all the energy
is normalized by the hoping energy $t (t = 1)$. The structural parameters of the asymmetrical
QW are fixed at $L_1 = 10\, a$, $W_1 = 10\, a$ and $L_2 = 6\, a$, with $a$ lattice spacing of the tight-
binding model. And the $z$ axis is chosen as the spin-quantized axis so that $|\uparrow> = (1, 0)^T$
represents the spin-up state and $|\downarrow> = (0, 1)^T$ denotes the spin-down state. The boundary
of the wire is determined by the hard-well confining potential. The total charge conductance
and the spin polarization of $z$-component are defined as $G^e = G_{\uparrow\uparrow} + G_{\uparrow\downarrow} + G_{\downarrow\downarrow} + G_{\downarrow\uparrow}$ and
$P_z = ((G_{\uparrow\uparrow} + G_{\uparrow\downarrow}) - (G_{\downarrow\downarrow} + G_{\downarrow\uparrow}))/G^e$, respectively.

Figure 2(a) shows the total charge conductance as function of the electron energy when
the spin-unpolarized electrons are injected into the considered system from the Left (L) lead
to the Right (R) lead (the forward biased case). When $E < 0.10$, the charge conductance
is zero since all the subbands of the quantum wire are evanescent modes. The step-like
structures are formed in the charge conductance with each step height being 2 in the straight
wire\textsuperscript{19}. But, when the electron energy $E > 0.10$, in the asymmetrical QW unlike the
straight wire, the charge conductance fluctuates in each step and the average heights of those
steps are reduced, due to the scattering at interfaces between the left and right quantum
wire of the investigated system. Furthermore, oscillations also emerge in the total charge
conductance, which may result from the multi-reflection at the interfaces between the left and right quantum
wire of the asymmetrical QW. The oscillation periodicity is related to
the wave vectors of the propagating modes so that the oscillations become apparent just
above the thresholds of the subbands where the wave vectors turn out to be smaller\textsuperscript{23}.

The SOC-induced Fano resonance dips also can be found in the charge conductance. The
corresponding spin polarization of Fig. 2(a) as show in Fig. 2(b), when $0.10 < E < 0.39$,
only the lowest one pair of subbands of the quantum wire are propagating modes, so there is
no spin polarized current\textsuperscript{24}. But when $E > 0.39$, both the inputting lead and outgoing lead
support two or more pairs of propagating modes and the subband intermixing induced by the Rashba SOC arises, resulting in the nonzero spin polarized current. It is worth to note that a valley-like structure [see the red rectangles in Fig. 2(a)] appears in the charge conductance when the emitting energy just near the threshold of the third pair of propagating modes in the right quantum wire, i.e., \( E = 0.83 \) and \( E = 1.36 \). This effect may be attributed to the bound state in the quantum wire couples to the conductance one, giving rise to a structure-induced Fano resonance\(^{21}\). Amazingly, at one of those Fano resonance (such as \( E = 0.83 \)), a large spin polarization \( |P_z| = 0.30 \) can be achieved in the outing lead. This effect may result from the two types of mirror symmetries (longitudinal and transverse direction symmetries) are all broken in the asymmetrical QW. Moreover, with the presence of Rashba SOC in the investigated system, the transparency of an initial spin-up electron is no longer equal to that of an initial spin-down electron. As a result, the spin polarization of the \( z \)-component is nonzero.

Figure 2(c) plots the total charge conductance as a function of the electron energy when electrons are injected into the considered structure from the lead R to L (the backward biased case). The total charge conductance is the same as in Fig. 2(a) due to the space-inversion symmetry of the asymmetrical QW. The corresponding spin polarization of Fig. 2(c) is plotted in Fig. 2(d). Interestingly, the magnitude of the spin polarization is equal to it in Fig. 2(b) but their signs are reversed. This may due to these two types of mirror symmetry are both destroyed, but the \( C_2 \) rotation symmetry is still reserved. Together with the time-reversal symmetry, we obtain the relation \( G_{\uparrow\uparrow}^{LR} = G_{RL}^{\downarrow\downarrow}, G_{\uparrow\downarrow}^{LR} = G_{RL}^{\downarrow\uparrow}, G_{\uparrow\downarrow}^{LR} = G_{RL}^{\downarrow\uparrow} \) and \( G_{\downarrow\uparrow}^{LR} = G_{RL}^{\uparrow\downarrow} \) [see Figs. 3(a) and 3(b)]. This means that for the forward and backward biased case, the magnitude of the spin polarization is equal, but their signs of the spin polarization are contrary. The characteristics in the spin polarization between the forward and backward transport directions can be utilized to devise a spin polarization direction switch device, in which the spin polarization direction can be switched by changing the direction of the external current, that is it can be rectified by all-electrical method.

In order to clarify this effect, the spin-dependent conductance for the forward and backward biased case as function of the electron energy is illustrated in Figs. 3(a) and 3(b), respectively. The strength of Rashba SOC \( t_{so} = 0.177 \). As show in Fig. 3(a), the spin-polarized components \( G_{\uparrow\uparrow}^{LR}(G_{LR}^{\downarrow\downarrow}) \) and \( G_{\downarrow\uparrow}^{LR}(G_{LR}^{\uparrow\downarrow}) \) exhibit a series of resonant structures because the Rashba SOC induces the spin splitting and results in a subband intermixing\(^{25}\).
At the energy near the bottom of the second to fourth subband \((E = 0.39, 0.83, \text{ and } 1.36, \text{ respectively})\), the spin conductances exhibit a sharp peak for \(G_{LR}^{↑↑}(G_{LR}^{↓↓})\) and a sharp dip for \(G_{LR}^{↑↓}(G_{LR}^{↓↑})\) in the forward biased case. This phenomenon is related to the details of the spin-dependent scattering mechanism of electron transport through the whole system configuration\(^{13}\). Due to the longitudinal and transversal symmetries are all broken in the asymmetrical QW, so the relations \(G_{LR(RL)}^{↑↑} = G_{LR(RL)}^{↓↓}\) and \(G_{LR(RL)}^{↑↓} = G_{LR(RL)}^{↓↑}\) cannot be guaranteed, leading to the nonzero spin polarization[as show in Figs. 2(b) and 2(d)] for the forward and backward biased case, respectively. Furthermore, the Hamiltonians of the asymmetrical QW are also invariant under \(C_2\) rotation. Therefore, from the \(C_2\)-rotation and time-reversal symmetries, we can find that the transmission probability of the spin-up (-down) electron from the lead L to R always equals that of the spin-down (-up) electron from the lead R to L. As a consequence, the magnitude of the spin polarization in the backward biased case is equal to it in the forward biased case and their signs are reversed as show in Figs. 2(b) and 2(d).

The LDOS of the asymmetrical QW for the forward and backward biases is shown in Figs. 5(a) and 5(b), respectively. The electron energy is taken to be \(E = 0.83\), and the strength of Rashba SOC \(t_{so} = 0.177\). As shown in Fig. 4(a), for the studied system in the forward biased case, two regular stripe appears in the left region of the asymmetrical QW that represents two pairs of propagating modes, whereas an obvious bound state is found to exist in the top of the right region of the asymmetrical QW. In this case, electrons are equivalent to transmit from a potential barrier region (the left region of the asymmetrical QW) to a potential well region (the right region of the asymmetrical QW) due to the transversal confining potential\(^{18}\). Thus electrons have a certain probability to stay in the right region of the asymmetrical QW. This is due to in the asymmetrical QW, different transverse modes can be mixed by corner scattering as well as by interface scattering at the interfaces between the left and right quantum wire of the investigated system. As a consequence, higher-index propagating modes are preferred to be populated inside the right region of the quantum wire\(^7\). Moreover, this bound state interacts with the Rashba SOC-induced effective magnetic, resulting in the transmission coefficient of the spin-up electron is injected from the inputting lead can be very different from that of the spin-down electron. Therefore, a large spin polarization can be achieved in the outgoing lead. However, in the backward biased case, as shown in Fig. 4(b), two regular stripe appears in the right region
of the asymmetrical QW and an obvious bound state is found to exist in the bottom of the right region of the asymmetrical QW. This may due to the $C_2$-rotation and time-reversal symmetries in the asymmetrical QW are all remained.

The above proposed spin polarization switch device is based on a perfectly clean system, where the influence of impurity scattering is not taken into account. But usually, in a realistic system contains a lot of impurities, and they are distributed randomly. Thus the effect of disorder should be considered in practical application. Now we show the feasibility of this device for a real application by analyzing the robustness of the spin conductance against the Anderson disorder. The total charge conductance and corresponding spin polarization as a function of the electron energy for different disorders $w$ are illustrated in Fig. 5. The Rashba SOC strength $t_{so} = 0.177$. The step-like charge conductance is destroyed with the increase of the disorder strength as show in Figs. 5(a) and 5(c), respectively. However, as shown in the lower panel in Fig. 5(b), the magnitude of the spin polarization around the thresholds of the propagating modes in the asymmetrical QW is still large, which indicates that the spin polarization can still survive even in the presence of strong disorder when electrons are injected from the forward direction. At the same time, the spin polarization is still very large for a strong disorder when electrons are injected from the backward direction, as shown in the lower panel in Fig. 5(d). The underlying physics could also be attributed to the different LDOS for the diverse bias directions even in the presence of disorder, as shown in Fig. 6. The disorder strength $w = 0.4$ and the other parameters are the same as that in Fig. 4. By comparing with Figs. 4(a) and (b), the LDOS is redistributed in the quantum wire due to the disorder-induced scattering. However, the salient features remain the same as that in Figs. 4(a) and (b).

In summary, a scheme of spin polarization direction switch is proposed by investigating the spin-dependent electron transport of an asymmetrical QW with the modulation of the Rashba SOC. It is shown that the magnitude of the spin-polarized current in the backward biased case is equal to it in the forward biased case but their signs are contrary. The underlying physics is revealed to originate from the symmetries in the longitudinal and transverse directions are all broken but $C_2$-rotation and time-reversal symmetries are still reserved. Further studies show that the spin polarization is robust against disorder, This results may provide an efficient method to generate an artificially controllable spin polarization direction in mesoscopic Rashba systems without applying an external magnetic field and without
attaching ferromagnetic contacts.

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Figures

FIG. 1: Schematic diagram of the asymmetrical quantum wire with Rashba SOC. the left and right quantum wires have the same length $L_1$ and a uniform width $W_1$.

FIG. 2: (Color online) The calculated total charge conductance and the corresponding spin polarization as a function of the electron energy. (a) The forward biased case. (b) The backward biased case. The Rashba SOC strength $t_{so} = 0.177$.

FIG. 3: (Color online) The calculated spin-dependent conductance as function of the electron energy when the spin-unpolarized electron is injected. (a) The forward biased case. (b) The backward biased case. The Rashba SOC strength $t_{so} = 0.177$.

FIG. 4: (Color online) The calculated LDOS of the quantum wire in the forward biased case (a) and in the backward biased case (b). The strength of Rashba SOC $t_{so}$ is fixed at 0.177. The electron energy $E = 0.83$. The arrow denotes the transport direction of electrons.

FIG. 5: (Color online) The calculated total charge conductance and the corresponding spin polarization as a function of the electron energy for different disorder strengths. (a) The forward biased case. (b) The backward biased case. The Rashba SOC strength $t_{so} = 0.177$.

FIG. 6: (Color online) The calculated LDOS of the disordered asymmetrical quantum wire in the forward biased case (a) and in the backward biased case (b). The strength of disorder $w = 0.4$, and other parameters are the same as that in Fig. 4. The arrow denotes the transport direction of electrons.
