A scheme for spin transistor with extremely large on/off current ratio

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Quantum wires with periodic local Rashba spin-orbit couplings are proposed for a higher performance of spin field-effect transistor. Fano-Rashba quantum interference due to the spin-dependent modulated structure gives rise to a broad energy range of vanishingly small transmission. Tuning Rashba spin-orbit couplings can provide the on- or off-currents with extremely large on/off current ratios even in the presence of a strong disorder.

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I. INTRODUCTION

Coherent manipulations of electron spin in nanoscale devices have made it promising to realize spintronics as well as quantum information processing and computation [1]. In 1990, especially, Datta and Das proposed a spin transistor in which electron spin can be manipulated by varying electric fields via spin-orbit couplings (SOCs) [2]. Spin transport have been intensively investigated in various types of such spin field-effect transistors (SFETs) in associations with spin filters or polarizers, spin currents, spin valves, and so on. However, the device working performances have not been studied yet much. Even the device performance rates in SFETs seem to be much lower than in charge field-effect transistors (FETs). Actually, for instance, the on/off current ratio is smaller than 10³ in a SFET with T-shaped structure [3] as well as that in a dual-gate SFET [4]. On the contrary, charge field-effect transistors have reached a higher performance rate. Indeed, recent high-mobility FETs using ZnO nanorods [3], poly(3-hexylthiophene) thin film [6], carbon nanotubes [7], and p-GaN/u-AlxGa1−xN/u-GaN junction heterostructure [8] have been demonstrated with on/off current ratios. Since spin coherence can be more fragile than charge decoherence, device disorders may also spoil the performance rate more significantly in SFETs than in charge field-effect transistors.

In this paper, we propose a SFET with high performance rate. To do this, we introduce a quantum wire with Rashba SOC modulations [9]. A local Rashba SOC in a quantum wire gives rise to a spin-dependent Fano effect that is the quantum interference of electron propagating through both the continuum energy channel and a localized electronic state resulting from the SOC. Due to the Rashba-Fano effect, electron transmission has asymmetric antiresonance dips [10, 11, 12]. Further, the periodic SOC modulation makes the energy range of vanishingly small electron transmission broader. This allows us a large on/off current ratio by tuning the SOC modulations. Even for a strong device disorder, the proposed SFET is shown to have higher performance rate with larger on/off current ratio than about 10⁵.

FIG. 1: Schematic view of quantum wire with periodic local Rashba couplings. The width and length of the quantum wire are Lw and L, respectively. The gray areas represent each Rashba region with its length La. The length of normal regions without SOC is Lb. In the text, an integer N denotes the number of Rashba regions.

II. MODEL AND FORMALISM

A quantum wire under consideration is shown in Fig. 1. The wire of length L is connected to two ideal leads. Its width is Lw, which determines the transverse propagating channels. The Rashba SOC is controlled in the gray regions with its length Lb, while the normal regions without the SOC has their size La. The number of Rashba regions is denoted by N. We apply a weak uniform perpendicular magnetic field, which guarantees that Landau levels are neglected, in the whole device including the leads. The Zeeman effect splits the on-site electronic energy into Vσ = σV0 with σ = ± for spin-up (↑) and -down (↓). To describe the quantum wire, then we introduce a tight-binding Hamiltonian with nearest-neighbor hopping:

$$H = \sum_{l,m,\sigma} c_{l,m,\sigma}^\dagger c_{l,m,\sigma} - t \sum_{l,m,\sigma} (c_{l+1,m,\sigma}^\dagger c_{l,m,\sigma} + H.C.) - t \sum_{l,m,\sigma} (c_{l+1,m,\sigma}^\dagger c_{l,m,\sigma} + H.C.) + H_R ,$$  (1)
where \((l, m)\) represent the site in the space representation of \((x, y)\). The on-site energy is \(\epsilon_{lm\sigma} = 4t + \sigma V_0\) with the hopping integral \(t = \hbar^2 / (2m^* a^2)\), where \(m^*\) and \(a\) are the electron effective mass and lattice constant, respectively. The Hamiltonian \(H_R\) describing the Rashba SOC modulation is given by

\[
H_R = \lambda \sum_{l,m,\sigma\sigma'} \left[ c_{l+1,m,\sigma}^\dagger c_{l,m,\sigma'} \sigma_\sigma^\sigma \right]
- \left[ c_{l,m+1,\sigma}^\dagger c_{l,m,\sigma'} \sigma_\sigma^\sigma \right] + \text{H.C.},
\]

where \(\lambda = \alpha / 2a\) is the Rashba SOC coefficient. \(\sigma_{x,y}\) are the Pauli matrices.

Within the Landauer-Büttiker framework [14], at zero temperature, the transport current is given by

\[
I = \frac{e}{h} \sum_{\sigma, \sigma'} i \int_{\mu_1}^{\mu_2} T^{\sigma\sigma'}(\varepsilon) d\varepsilon,
\]

where the spin-resolved transmission amplitude [14] is

\[
T^{\sigma\sigma'}(\varepsilon) = \text{Tr} \left[ \Gamma_1^\dagger \mathcal{G}^{\sigma\sigma'}_{1M}(\varepsilon) \Gamma_M^\dagger \mathcal{G}^{\sigma\sigma'}_{M1}(\varepsilon) \right],
\]

with the tunnel couplings \(\Gamma_{1(M)}\) between the wire and the leads. \(\mathcal{G}^{\sigma\sigma'}_{1M}\) and \(\mathcal{G}^{\sigma\sigma'}_{M1}\) are the retarded and advanced Green’s functions [13], respectively. Here, \(\mu_1\) and \(\mu_2\) are the Fermi energy of the left (right) lead.

The energies of the transverse propagating channels are given by \(\epsilon_n = 2t \{ 1 - \cos[n\pi/(L_w / a + 1)] \}\) with the channel index \(n\). We consider the lowest energy channel \(n = 1\). In our numerical calculation, the lowest energy is \(\epsilon_1 \approx 0.081t\) for \(L_w = 10a\). It is assumed that only spin-down electrons can propagate into or out of the wire structure. To make it sure, the Fermi energy \(E_F\) can be adjusted as the energy between \(\epsilon_1 - V_0\) and \(\epsilon_1 + V_0\). Thus, only \(T^{\uparrow\downarrow}\) is responsible for electron transport, i.e., the total transmission amplitude becomes \(T = T^{\uparrow\downarrow}\).

### III. RESULTS

In Fig. 2, we plot the transmission amplitude as a function of Fermi energy for \(N = 9\) and \(\lambda = 0.13t\). Numerical parameters were chosen as \(V_0 = 0.01t\), \(L_b = 10a\), \(L_a = 3L_b\) and \(L_w = L_b\). Note that due to the serial SOC modulations the electron transmission is vanishingly small in a wide range of energy. Roughly, the energy range is from \(E_F = 0.076t\) to \(E_F = 0.084t\). This can play a significant role for the device performance, i.e., particularly the off current. To show clearly the effects of periodic Rashba SOC modulations, in Fig. 3 (a), the transmission amplitudes are plotted for \(N = 1, 3, 5, 7, 9,\) and \(12\). It is shown that the gap where the vanishingly small transmission happens becomes wider and deeper as the number of Rashba SOC regions increases. Also, inside the gap, Fano-Rashba antiresonances appear to give a much smaller transmission through the quantum wire, which can provide smaller off currents. Further, as the SOC strength decreases, one find a high transmission within the gap. In Fig. 3 (b), the high transmission for \(\lambda = 0.08t\) is shown in the energy range of low transmission for \(\lambda = 0.13t\). The high transmission in the gap does not change very much as the number of SOC regions increases. Then, this may provide a high current as an on current.
FIG. 4: (Color online) Spin transport current as a function of the Rashba SOC strength for $N = 9$. The voltage bias window is chosen as $[0.078t, 0.082t]$ within the gap in Fig. 2. Other parameters are $L_b = 10a$, $L_a = 3L_b$ and $L_w = L_b$. The “on” and “off” indicate the high and low currents for the device performance rate.

FIG. 5: (Color online) Transmittances $T$ as a function of the Fermi energy of the leads for various Anderson disorder strengths $W$. For $N = 3$, (a) $\lambda = 0.13t$ (off current) and (b) $\lambda = 0.08t$ (on current). For $N = 9$, (c) $\lambda = 0.13t$ (off current) and (d) $\lambda = 0.08t$ (on current).

In Fig. 4, the spin transport current is plotted as a function of the SOC strength $\lambda$ for the voltage bias window $[0.078t, 0.082t]$. It should be noted that there are three regimes of spin current as the SOC varies, i.e., (i) high current regime ($0 \leq \lambda \lesssim 0.1 t$), (ii) transit current regime ($0.1 t \lesssim \lambda \lesssim 0.12 t$), and (iii) low current regime ($0.12 t \lesssim \lambda$). For instance, from the numerical calculation, we obtain the on/off current ratios: $1 \times 10^4$ for $N = 3$, $2.7 \times 10^{12}$ for $N = 9$, and $6.8 \times 10^{15}$ for $N = 12$. Then, our SFETs show the high device performance with the on/off current ratio bigger than that of EFTs in Refs. 2, 6, 8, 9 and 16.

Device disorders can destroy spin coherence. Thus, the device performance may be spoiled severely due to the disorders. Figure 5 shows the effects of the Anderson disorders on electron transmission in (a) and (b) for $N = 3$ and in (c) and (d) for $N = 9$. The transmission amplitudes were averaged over $1 \times 10^4$ configurations for $N = 3$ and $3 \times 10^4$ configurations for $N = 9$. It is shown that the vanishingly small transmissions within the gaps become larger as the disorder strength $W$ increases. However, the transmission amplitudes are still smaller than $T \lesssim 10^{-5}$ even for the stronger disorder $W = 0.04t$, which guarantees a high performance of our SFETs. This is clearly shown in Fig. 6. The on/off current ratio decreases as the Anderson disorder strength becomes stronger. For $N = 3$, relatively, a mild spoil of device performance occurs because the ratios are $I_{on}/I_{off} \simeq 1 \times 10^4$ for $W = 0.0$ and $I_{on}/I_{off} \simeq 0.89 \times 10^3$ for $W = 0.04t$. For $N = 9$, the quantum wire without the disorder has a extremely large on/off current ratio $I_{on}/I_{off} \simeq 2.7 \times 10^{12}$. The strong disorder $W = 0.04t$ gives rise to strong spin decoherence and the on/off current ratio becomes $I_{on}/I_{off} \simeq 3.0 \times 10^5$. However, this shows that the device performance is still good enough for a SFET. As a result, the quantum wires with the spin-dependent modulations can provide a high performance SFET even though the strong disorder destroys spin coherence severely.

IV. SUMMARY

In summary, we have proposed the quantum wires with periodic local Rashba SOCs as a spin transistor. The device shows a good device performance as a SEFT with extremely large on/off current ratios, although strong device disorders destroy spin coherence.

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