Spin relaxation and tunnel magnetoresistance of a ferromagnet / superconductor / ferromagnet single-electron tunneling transistor

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Abstract

We theoretically study the spin relaxation and tunnel magnetoresistance(TMR) of ferromagnet / superconductor / ferromagnet single-electron tunneling transistors with a special attention to the parity effect. We show that the spin accumulation is forbidden in the plateau region even at finite bias voltage. However, the information of injected spin is carried by an excess electron and TMR exists. We also show that the TMR increases with decreasing the size of the superconducting island.

Key words: spin relaxation; parity effect; tunnel magnetoresistance; spin-dependent transport

Recently much attention has been devoted to the SET transistor with a superconducting island and normal conducting electrodes(N/S/N) [1]. The research on the N/S/N SET transistor has focused primary on the charge degrees of freedom of electrons, by contrast, its spin degrees of freedom have not yet received much attention. However, an increasing number of researches on spin-electronics show that the spin of electron offers unique possibilities for finding novel mechanisms for future spin-electronic devices [2].

In this article, we theoretically study the spin dependent transport in ferromagnet / superconductor / ferromagnet(F/S/F) SET transistors with a special attention to the parity effect. The schematic diagram of a F/S/F SET transistor is shown in Fig. 1 (a). For simplicity we assume that the insulating barriers of junctions 1(left) and 2(right) are the same; we subsequently set $C_1 = C_2 \equiv C$. We also assume that charging energy E_c is larger than the superconducting gap energy Δ and the left and right electrodes are made of the same material with the spin polarization P.

The tunneling of an electron with spin σ through the i-th junction costs the energy $E_i^{\pm}(n)$, where n is the number of excess electrons of the initial state in the island, and the superscripts $\pm$ implies that the number of excess electrons in the final state is $n \pm 1$. The Coulomb blockade(CB) regions are the rhombuses determined by $E_1^+(n), E_1^-(n), E_2^+(n)$, and $E_2^-(n) \geq 0$ as shown in Fig. 1 (b). Adjacent to the CB region, we have a so-called "plateau region" where the tunneling current is dominated by the tunneling rate through one junction which behaves like a bottleneck of the tunneling current. In the plateau region the tunneling current

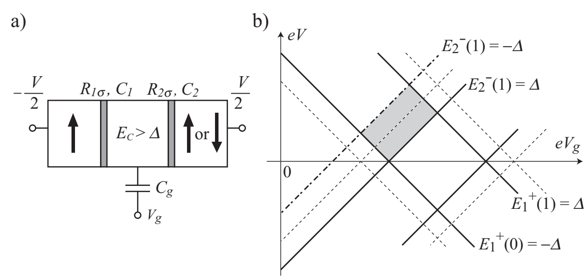

Fig. 1. a)Schematic diagram of a F/S/F SET transistor. The arrows indicate the magnetizations of the left and right electrodes. b) The gate and bias voltage diagram of a symmetric SET transistors. Solid lines indicate the boundaries for the F/S/F SET transistor. Thin dashed lines are the boundaries for the F/N/F SET transistor ($\Delta = 0$). The dot-dashed line indicates a boundary of the plateau region.

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is carried by the even and the odd states in the following manner. An electron with spin σ tunnels into the island from the left or right electrode. While staying in the island, the spin of the electron relaxes due to the spin orbit interaction, and/or the hyperfine contact interaction [4]. After a certain time period determined by the transition rate from the odd to the even state, the electron tunnels out of the island. Therefore, no spin accumulation occurs even at the finite bias voltage. Outside the plateau region, continuous quasiparticle states contribute to the tunneling current and the spin accumulation can exist[3].

We consider the tunneling current and TMR in the plateau region, for example, indicated by shade in Fig. 1 (b). In this region, the following three states are available: $|0\rangle$ three is no excess electron in the island, $|\uparrow\rangle$ there is one up-spin excess electron in the island, $|\downarrow\rangle$ there is one down-spin excess electron in the island. The transition rate from $|0\rangle$ to $|\sigma\rangle$ is given by

$$\Gamma_\sigma^+ = \frac{1}{e^2 R_{1\sigma}} \sqrt{E_1^+(0)^2 - \Delta^2}, \tag{1}$$

and the transition rate from $|\sigma\rangle$ to $|0\rangle$ is

$$\Gamma_\sigma^- = \frac{d}{e^2 R_{2\sigma}}, \tag{2}$$

where d is the average level spacing of the island. The transition rate between $|\uparrow\rangle$ and $|\downarrow\rangle$ is given by the spin relaxation rate η. The tunneling current is obtained by solving the master equation. The TMR is defined by the formula $TMR = 1 - I_A/I_F$, where subscripts F and A represents the ferromagnetic and antiferromagnetic alignment of the magnetization. A straightforward calculation gives

$$TMR = \frac{(\alpha-1)^2}{\zeta(\alpha+1)(\beta+2)+\alpha^2+\alpha\beta+1}, \tag{3}$$

where $\alpha \equiv R_m/R_M$, $\beta \equiv \Gamma_M^-/\Gamma_M^+$,$\zeta \equiv \eta/\Gamma_M^-$. Here the subscript $M(m)$ represents majority(minority) spin band. The TMR is a monotonically decreasing function of ζ and the spin relaxation rate of an excess electron η can be estimated from the TMR by fitting the experimental data. If there is no spin relaxation process in the island, $\zeta = 0$, the TMR is approximately given by $TMR \simeq 2P^2/(1+P^2)$.

The fact that the TMR depends on the spin relaxation rate η via its normalized value ζ means that how much the spin information is transmitted is determined by the competition between the spin relaxation rate and the transition rate from the odd to the even state. In the plateau region the inverse of the transition rate $\Gamma_{M(m)}^-$ describes how long the excess electron with majority(minority) spin stays in the island. Therefore, the normalized spin relaxation rate ζ represents the probability that the electron with the majority spin tunnels out of the island holding its spin direction and the TMR is a function of ζ.

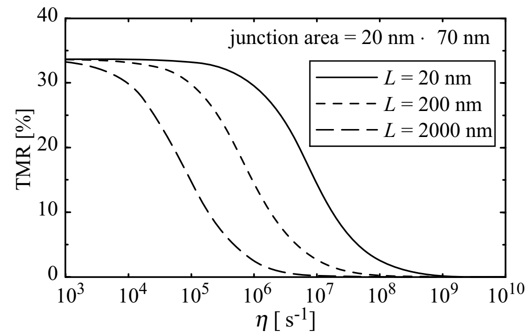

Fig. 2. TMR of the F/S/F SET with $P = 0.45$ is plotted against the spin relaxation rate η. The area of the junction is fixed at 20nm $\times$ 70 nm[1] and the junction resistance $R_M = 1$ MΩ for L=2000 nm. We assume that Δ=0.18 meV (Aluminum), E_C=8.0meV and $d = 3.0 \times 10^{-5}$ meV and the working point is set to the center of the plateau region.

In the WKB approximation, the square of the tunneling matrix element $|T|^2$ is inversely proportional to the length of the island L. If the junction parameters other than L are kept fixed, the density of states $N_\sigma^I (= 1/d)$ is proportional to L. In this situation, the transition rate Γ_σ^+ does not depend on L since the size dependences of $|T|^2$ and N_σ^I in R_σ^1 cancel out. On the contrary, Γ_σ^- is inversely proportional to L. The normalized spin relaxation rate ζ decreases and therefore the TMR increases with decreasing L. In Fig. 2 the TMR of the F/S/F SET transistor with $P = 0.45$ is plotted against the spin relaxation rate η for various values of L. For the spin relaxation rate $\eta = 10^7$ s^{-1}, which is of the same order as that caused by the hyperfine contact interaction [4], the TMR is 0.26, 2.4, and 15 % for $L =$ 2000, 200, and 20 nm, respectively.

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