Journal of Magnetism and Magnetic Materials 446 (2018) 150–154

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Research articles

The effects of changing the electrodes temperature on the tunnel magnetoresistance in the ferromagnetic single electron transistor

N. Ahmadi [a,*], N. Pourali [b], E. Kavaz [c]

[a] Department of Physics, Marand Branch, Islamic Azad university, Marand, Iran
[b] Physics Department, Faculty of Science, Sahand University of Technology, 51335-1996 Tabriz, Iran
[c] Department of Physics, Faculty of Science, Ataturk University, Erzurum, Turkey

ARTICLE INFO

Article history:
Received 16 February 2017
Accepted 8 September 2017
Available online 10 September 2017

Keywords:
Transistor
Single electron
Ferromagnetic
Tunnel magnetoresistance
Electrodes temperature

ABSTRACT

Ferromagnetic single electron transistor with electrodes having different temperatures is investigated and the effects of changing electrodes temperature on TMR of system are studied. A modified orthodox theory is used to study the system and to calculate the electron tunneling transition rate. The results show that the temperature of electrodes can be an effective tool to control and tune the tunnel magnetoresistance of FM-SET. Also, the effects of parameters such as resistance ratio of junctions, magnetic polarization and spin relaxation time on the behaviour of the system are studied.

1. Introduction

With the advancement of the technology it is possible to fabricate nanometer-scaled devices and observing the single electron or single electron tunnelling effects. These devices are known as single-electron nanodevices [1]. A simple and attractive single-electron nanodevice is single electron transistor (SET) [2–4], a small double-tunnel junction system that its central electrode is connected to a controlling gate voltage. Due to low power consumption and small size it has found extensive applications in different areas of industry such as thermometry, single-electron pumping, charge detection, and detection of nanoelectromechanical motion [5–11].

SET with the ferromagnetic electrodes is named ferromagnetic single electron transistor (FM-SET) that due to its potential applications in spintronic devices is a very active area of research. In FM-SET when the relative orientations of the electrodes magnetization are changed from antiparallel to parallel alignment, the total tunnel resistance of the device decreases. This magnetic depended effect that is known as tunnel magnetoresistance (TMR) is related to spin dependence of the electron's transition rates. Decrease in the island size leads to appearance of new spin-dependent phenomena such as oscillations in TMR with increasing bias voltage, spin accumulation and enhancement of TMR in the Coulomb blockade regime.

A lot of researches have been devoted to the study of the ferromagnetic SET. Ono et al. were first ones who reported the enhancement of the TMR in a Ni/NiO/Co/NiO/Ni-based ferromagnetic SET and justified this effect by quantum fluctuation of charge and spin polarizations of the island and the outer electrodes[12,13]. Results of research carried out by Brataas et al. showed that in the small island with large energy spacing the spin accumulation is remarkable and partial conductance grows with enhancement of spin relaxation rate. Also the spin accumulation in the island causes increase of TMR [14]. The subsequent works [15] revealed that the TMR ratio as a function of the bias voltage shows the dips which are directly results of the induced separation of Fermi levels [15]. TMR oscillates with gate voltage and the its amplitude can be adjusted by changing the bias voltage [16]. Also non-equilibrium spin accumulation in the island is depended to the junction resistance and junction area [17]. A comprehensive study was done by Weymann and Barnas [18]. They studied the system both in fast and slow spin relaxation limit and investigated the crossover between these limits. The results showed that TMR dependency on the bias and the gate voltage is strongly affected by difference between spin asymmetry of tunneling rates in the tunnel junctions. Also the dependency of spin polarization of the current, TMR and spin accumulation on the gate voltage were analyzed.

When the size of the island in the SET decreases, its temperature begin to be affected by electronic current and reverse.

---

[*] Corresponding author.
E-mail address: n.ahmadi@marandiau.ac.ir (N. Ahmadi).

http://dx.doi.org/10.1016/j.jmmm.2017.09.019

Therefore, the heating consideration in the study of the system become worthwhile. The effects of heating in SET in the regime of single-electron tunneling have been studied in the early papers [11,19]. Recently Laakso et al. included the cotunneling in study of SET heating [20]. The results showed that the transport of the electron is separated to three regime: single electron dominated, cotunneling dominated, and competition regime where the cotunneling and the single electron tunneling compete together. Due to the inclusion of cotunneling, the self-heated SET showed specific phenomena such as temperature fluctuation and slow current noise with a large Fano factor. These effects were strongly observable in crossover region between pure sequential tunneling and competition dominated regimes. They also showed that for SETs having small island the expectation and the most probable values of temperature are different from each other [21]. This is because of existing a tail in the probability distribution of temperature that extended towards high temperatures. It in turn originates from the exponential temperature sensitivity of the electric current.

Although the ferromagnetic SET and heating effects on SET have already been studied separately, but there is no research considering heating effects in ferromagnetic single electron transistor and in all of the theoretical considerations of the FM-SET have been assumed that the electron temperature is constant and equal to the temperature of the substrate. Therefore, in this paper we report the study of the effects of electrodes temperature variation on electronic transport and TMR in FM-SET. We restrict our to single electron regime and ignore the higher-order tunneling processes(so-called cotunneling). It noted that in this regime the resistance of tunnel junction must be lager than the quantum resistance $R_i \gg h/e^2$ $(i = 1, 2)$. Also, we assume that spin relaxation is sufficiently slow as there is a spin accumulation in the island and the spin splitting of chemical potential is established. In following section we introduce the theoretical methods utilized in this paper. The results of numerical simulation are presented and discussed in Sec. III and the paper is concluded in Sec. IV with a summary of the main findings.

2. Model

Schematic structure of SET considered in this work is shown in Fig. 1. The system is a double-tunnel-junction with capacitances C_1 and C_2 that its middle electrode is coupled to gate through a capacitance C_g. A voltage source is attached to each electrode (the source, the drain, and the gate) and a background charge Q_0 is considered for the island. We assume that the outer electrodes are ferromagnetic and their temperature is different from that of the nonmagnetic island. The total resistance of the ferromagnetic tunnel junctions is separated to partial resistances for 'up' and 'down' spins as:

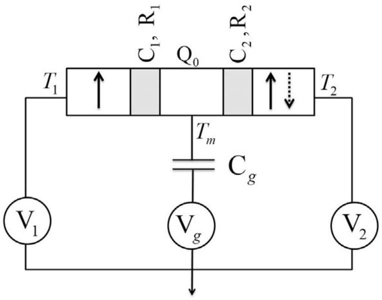

Fig. 1. Schematic of a ferromagnetic single-electron transistor with electrodes having different temperatures.

$$R_{\rm i} = \left(1/R_{\rm i}^u + 1/R_{\rm i}^d\right)^{-1}, \tag{1}$$

where partial resistances depend on the magnetic polarization P_i as $R_{\rm i}^u = 2R_{\rm i}/(1 + P_{\rm i})$ and $R_{\rm i}^d = 2R_{\rm i}/(1 - P_{\rm i})$. The signs of polarizations can determine magnetic configuration of the system. As for parallel magnetization we have $(p_1p_2 > 0)$ while in antiparallel configuration one of the magnetization directions is reversed $(p_1p_2 < 0)$. The average electric current flowing through each junction in the direction from tunnel junction 1 to tunnel junction 2 can be calculated as:

$$I_1(V) = \sum_{n,s} e\left[\Gamma_1^{s+}(n,V) - \Gamma_1^{s-}(n,V)\right]p(n,V) \tag{2}$$

$$I_2(V) = \sum_{n,s} e\left[\Gamma_2^{s-}(n,V) - \Gamma_2^{s+}(n,V)\right]p(n,V), \tag{3}$$

where e is the positive elementary charge, $\Gamma_{\rm i}^{s\pm}$ is the spin-dependent tunneling rate to (+) and off (−) the island through the ith junction (s denotes up (u) or down (d) spin electrons) and $p(n,V)$ is the probability that there are n extra electrons on the middle electrode in applied voltage V, that is determined by the master equation,

$$dp(n,V)/dt = \sum_{\rm i,s,\pm} p(n \pm 1, V)\Gamma_{\rm i}^{s\mp}(n \pm 1, V) - \sum_{\rm i,s,\pm} p(n,V)\Gamma_{\rm i}^{s\pm}(n,V). \tag{4}$$

For the dc characteristics of the system the stationary solution $(dp(n)/dt = 0)$ is acceptable and a significant simplification can be achieved by symmetry considerations [22]. As under normalized condition $\sum_{n=-\infty}^{\infty} p(n) = 1$, the probability distribution function is given by

$$p(n,V) = \frac{\left(\prod_{i=-\infty}^{n-1} x(i,V)\right)\left(\prod_{i=n+1}^{+\infty} y(i,V)\right)}{\sum_{j=-\infty}^{+\infty}\left(\prod_{i=-\infty}^{j-1} x(i,V)\right)\left(\prod_{i=j+1}^{+\infty} y(i,V)\right)}, \tag{5}$$

where $x(n,V) = \Gamma_1^{u+}(n,V) + \Gamma_1^{d+}(n,V) + \Gamma_2^{u+}(n,V) + \Gamma_2^{d+}(n,V)$ and $y(n) = \Gamma_1^{u-}(n,V) + \Gamma_1^{d-}(n,V) + \Gamma_2^{u-}(n,V) + \Gamma_2^{d-}(n,V)$. To calculate the electron tunneling rate in the tunnel junctions with electrodes having different temperatures we use the golden rule and assume that the energy relaxation in the electrodes is fast enough to produce the Fermi distribution $f(E,T) = 1/[1 + \exp(E/T)]$ and the densities of states and the tunneling matrix element are independent of the energy. As it results

$$\Gamma_{\rm i}^{s+}(\Delta E_{\rm i}^{s+}, T_{\rm i}, T_{\rm m}, R_{\rm i}^s) = \tfrac{1}{e^2 R_{\rm i}^s}\int_{-\infty}^{\infty} f(\varepsilon, T_{\rm i})\left[1 - f(\varepsilon + \Delta E_{\rm i}^{s+}, T_{\rm m})\right]d\varepsilon, \tag{6}$$

$$\Gamma_{\rm i}^{s-}(\Delta E_{\rm i}^{s-}, T_{\rm m}, T_{\rm i}, R_{\rm i}^s) = \tfrac{1}{e^2 R_{\rm i}^s}\int_{-\infty}^{\infty} f(\varepsilon, T_{\rm m})\left[1 - f(\varepsilon - \Delta E_{\rm i}^{s-}, T_{\rm i})\right]d\varepsilon. \tag{7}$$

Here T_i $(i = 1, 2)$ and T_m are the temperatures of the outer and central electrodes, respectively, and spin-dependent energy gains $\Delta E_{\rm i}^{u\pm}$ and $\Delta E_{\rm i}^{d\pm}$ are given by

$$\Delta E_{\rm i}^{u\pm} = -e^2/(2C_\Sigma) \pm [eV_{\rm i} - eV(n)] \mp \Delta E_F, \tag{8}$$

$$\Delta E_{\rm i}^{d\pm} = -e^2/(2C_\Sigma) \pm [eV_{\rm i} - eV(n)] \pm \Delta E_F, \tag{9}$$

where $C_\Sigma = C_1 + C_2 + C_g$ is the total capacitance of the island, $V(n) = (ne + Q_0 + C_1V_1 + C_2V_2 + C_gV_g)/C_\Sigma$ is the voltage of the island for the relevant charge state with n being an integer that specifies the number of elementary charges that have been added to the island, and ΔE_F is the spin shift of the Fermi energy. When the energy relaxation of electrons in the island is much faster than the spin relaxation, the spin accumulation occurs on the island and there is a spin splitting of the energy that can be calculated self-consistently by following equation [23]: