THEORETICAL ANALYSIS OF SPIN-DEPENDENT TRANSPORT IN FERROMAGNETIC SINGLE-ELECTRON TRANSISTOR WITH NON-COLLINEAR MAGNETIZATIONS: THE SEQUENTIAL TUNNELING REGIME

Justyna Wiśniewska[1], Ireneusz Weymann[1], Józef Barnaś[1,2]

[1] Institute of Physics, Adam Mickiewicz University, Umultowska 85, 61-614 Poznań, Poland

[2] Institute of Molecular Physics, Polish Academy of Sciences, M. Smoluchowskiego 17, 60-179 Poznań, Poland

ABSTRACT

Spin-dependent electronic transport in a ferromagnetic single-electron transistor (FM SET) is studied theoretically in the sequential tunneling regime [1]. Two external electrodes and the central part (island) of the device are ferromagnetic with the corresponding magnetizations being generally non-collinear. It is assumed that spin relaxation processes on the island are sufficiently fast to neglect spin accumulation. Based on the real time diagrammatic approach [2-4], we developed a computer algorithm that calculates transport characteristics in the first order (sequential) tunneling regime. The relevant probabilities of different charge states have been determined from the appropriate master equations. Tunneling current and tunnel magnetoresistance (TMR) are calculated as a function of the bias and gate voltages, and for arbitrary magnetic configuration of the system. It is shown that electric current and (TMR) strongly depend on the angle between magnetizations. This dependence follows from asymmetry between the spin majority and spin-minority electron bands in ferromagnetic metals. Numerical results on transport properties of a FM SET coincide with those derived from the master equation approach with transition rates determined from the Fermi golden rule [5,6].

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MODEL

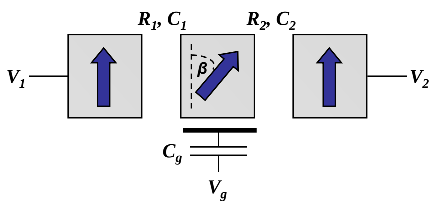


Fig.1. Schematic diagram of the ferromagnetic single-electron transistor consisting of two ferromagnetic external electrodes and ferromagnetic central electrode (island) between them, while the gate is nonmagnetic. Magnetization of the island is arbitrary orientated. The parameters are as indicated in the figure.

THEORY

ASSUMPTIONS AND REQUIREMENTS

- we take into account only sequential tunneling processes
- the resistances of both junctions have to be much bigger than the quantum resistance:

$$R_r >> R_Q = \frac{h}{e^2} = 25.81 k\Omega, \qquad (r = 1,2)$$

- the charging energy should be considerably larger than the thermal energy:

$$\frac{e^2}{2C} >> k_B T$$

- spin relaxation time of electrons on the island is shorter than the time between two successive tunneling processes – no spin accumulation

BASIC ELECTROSTATICS

- charging energy of the system:

$$E_{ch}(N,V) = \frac{\left(Ne - C_1V_1 - C_2V_2 - C_gV_g\right)^2}{2C}$$

where $C = C_1 + C_2 + C_g$ is the total capacitance of the island

- each tunneling line of irreducible diagrams on the Keldysh contour (which indicate respective tunneling processe of a single electron with spin σ between the island and the electrode) gives the Fermi golden-rule rate [1-3]:

$$\alpha_r^{\pm,\sigma}(\omega) = \pm\alpha_0^{r,\sigma} \frac{\omega-\mu_r}{e^{\pm\beta(\omega-\mu_r)}-1} \sim \cos^2\frac{\beta}{2}\frac{1}{R_r^p} + 2\sin^2\frac{\beta}{2}\frac{1}{R_{r,\sigma}^{ap}}$$

where $\alpha_0^{r,\sigma} = \frac{h}{4\pi^2 e^2}\frac{1}{R_{r,\sigma}} = \frac{R_Q}{4\pi^2 R_{r,\sigma}}$, $R_{r,\sigma}$ denotes spin-dependent resistance of the junction, ω is the energy of tunneling line in diagram and $R_{r,\sigma}^{ap} = \sqrt{R_{r,\sigma}^p R_{r,\bar{\sigma}}^p}$, $R_r^p = R_{r,\sigma}^p + R_{r,\bar{\sigma}}^p$

- the relevant occupation probabilities of different charge states are determined from the generalized master equation in the Liouville space:

$$0 = \sum_{\chi'} P_{\chi'} \Sigma_{\chi',\chi}$$

where $\Sigma_{\chi',\chi}(t',t)$ is the generalized transition rate from a state χ' (initial charge state of a diagram) at time t' to state χ (final charge state of a diagram) at time t

- the stationary current flowing through the junction r is given by:

$$I_r = -\frac{ie}{\hbar}\sum_{\chi,\chi'} P_{\chi'} \Sigma_{\chi',\chi}^{r+} = \frac{ie}{\hbar}\sum_{\chi,\chi'} P_{\chi'} \Sigma_{\chi',\chi}^{r-}$$

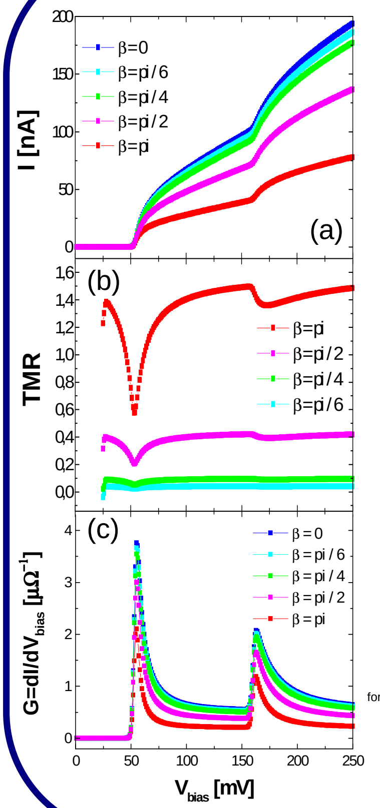
where $\Sigma_{\chi',\chi}(t',t) = \sum_j \left\{\Sigma_{\chi',\chi}^{r+}(t',t) + \Sigma_{\chi',\chi}^{r-}(t',t)\right\}$

- the tunneling magnetoresistance (TMR effect) is expressed as:

$$TMR = \frac{I(\beta=0)}{I(\beta)} - 1 = \frac{I_p}{I_{angle}} - 1$$

where I_p is the current flowing in the parallel configuration and I_{angle} is the current flowing in the non-collinear situation beetwen magnetizations (β is the angle of rotation of the magnetic moment of the island)

NUMERICAL RESULTS



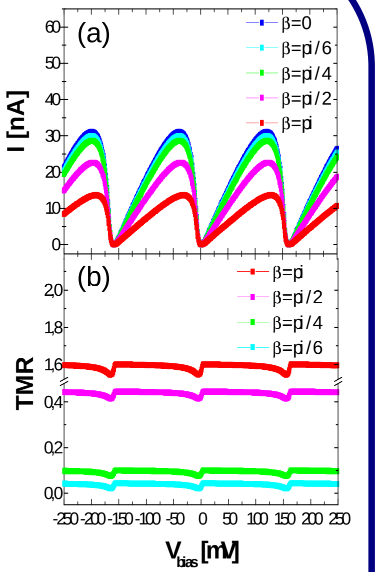


Fig.3. The electric current (a) and TMR (b) as a function of the gate voltage, calculated for the bias voltage V = 50mV. The other parameters are the same as in Fig.2.

Fig.2. The bias voltage dependence of electric current (a), differential conductance (c), as well as the resulting TMR (b) for different magnetic configurations of the system. The parameters assumed in numerical calculations are: $C_1 = C_2 = C_g = 1aF$, $T = 4.2K$ and $V_g = 0$, while the barrier resistances: $R_1^{p,\uparrow} = 25M\Omega$, $R_1^{p,\downarrow} = 1M\Omega$, $R_2^{p,\uparrow} = 0.5M\Omega$, $R_2^{p,\downarrow} = 0.1M\Omega$.

CONCLUSIONS

- the dependence of the current on the bias voltage is nonlinear and presents characteristic Coulomb staircases (fig.2a)
- the sequential current is blocked for small bias voltages – the Coulomb blockade effect (fig.2a)
- the currents flowing in two magnetic configurations – parallel and non-collinear between magnetizations (fig.2a), are different and this difference gives rise to the nonzero tunnel magnetoresistance (fig.2b)
- the amplitude of tunnel magnetoresistance oscillations decreases with increasing the bias voltage (fig.2b)
- the dependence of differential conductance on the bias voltage (fig.2c) shows peaks corresponding to Coulomb steps in the corresponding currents (fig.2a)
- the dependence of the current on the gate voltage presents characteristic Coulomb oscillations (fig.3a)
- Coulomb oscillations of the current lead to the oscillatory behaviour of the TMR effect (fig.3b)
- the dependences of the current on the bias and gate voltages show that the current decreases as rotation of the magnetization of the island increases (fig.2a and 3a)
- the magnitude of the TMR effect increases as angle between magnetizations increases (fig.2b and 3b)
- all the transport characteristics – the current, TMR and differential conductance, strongly depend on the magnetic configuration of the system