Spin Accumulation in Ferromagnetic Single-Electron Transistors

J. Martinek [a,b,c,1], J. Barnaś [c,d], S. Maekawa [b], H. Schoeller [e], G. Schön [a]

[a] *Institut für Theoretische Festkörperphysik, Universität Karlsruhe, 76128 Karlsruhe, Germany*
[b] *Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan*
[c] *Institute of Molecular Physics, Polish Academy of Sciences, ul. M. Smoluchowskiego 17, 60-179 Poznan, Poland*
[d] *Department of Physics, Adam Mickiewicz University, ul Umultowska 85, 61-614 Poznan, Poland*
[e] *Institut fur Theoretische Physik A, RWTH Aachen, 52056 Aachen, Germany*

Abstract

We propose a new method of direct detection of spin accumulation, which overcomes difficulties met in earlier measurements. A spin dependent current in a single-electron transistor with ferromagnetic electrodes leads to a nonequilibrium spin accumulation on the metallic island. Owing to the charging energy, the resulting spin-splitting of the electrochemical potential of the island can be detected from the spacing between two resonances in the current-voltage characteristics. The effect can be observed both in the sequential and cotunneling limits.

Key words: spin accumulation; single-electron transistor; spin-dependent transport

Non-equilibrium spin accumulation [1] due to spin-polarized electronic transport occurs in inhomogeneous spin-polarized electron systems and is related to a difference in local electrochemical potentials for electrons with opposite spin orientations ($\mu_\uparrow - \mu_\downarrow$). Such a difference may be created, e.g., by spin injection from ferromagnetic to normal metals, as predicted theoretically and also observed experimentally [1].

There are several experimental techniques by which the spin accumulation can be detected indirectly [1]. The question whether spin splitting of the electrochemical potential can be observed directly, for instance by spectroscopic methods analogous to tunneling spectroscopy for superconducting gap, is still open. In this paper we show how the spin splitting can be evaluated from some peculiarities in the transport characteristics of ferromagnetic single-electron transistors (FM SET's) with a normal metallic island.

Spin-dependent transport in ferromagnetic double-barrier tunnel junctions was recently studied both experimentally [2] and theoretically in the sequential, and cotunneling [3] regimes. We use the technique which is an extension of the real-time diagrammatic formalism developed for nonmagnetic junctions [4], and which is applicable for arbitrary temperature and arbitrary transport voltage.

The electric current I in the sequential tunneling limit is given by $I^{(1)} = \sum_\sigma I^{(1)}_{\mathrm{L}\sigma} = -\sum_\sigma I^{(1)}_{\mathrm{R}\sigma}$, with [5]

$$I^{(1)}_{\mathrm{r}\sigma} = \frac{4\pi^2 e}{h} \sum_n \left[p^{(0)}_n + p^{(0)}_{n+1} \right] \times \frac{\alpha^-(\Delta_n)\,\alpha^+_{\mathrm{r}\sigma}(\Delta_n) - \alpha^+(\Delta_n)\,\alpha^-_{\mathrm{r}\sigma}(\Delta_n)}{\alpha(\Delta_n)}\,, \qquad (1)$$

where $\Delta_n = E_{\mathrm{ch}}(n+1) - E_{\mathrm{ch}}(n)$, and the parameters $\alpha^\pm_{\mathrm{r}\sigma}(\epsilon)$ are the forward and backward propagators on the Keldysh contour in the Fourier space, $\alpha^\pm_{\mathrm{r}\sigma}(\epsilon) = \pm\alpha^0_{\mathrm{r}\sigma} \frac{\epsilon - \Delta\mu_{\mathrm{r}\sigma}}{\exp[\pm\beta(\epsilon-\Delta\mu_{\mathrm{r}\sigma})]-1}$, where $\alpha^0_{\mathrm{r}\sigma} = h/(4\pi^2 e^2 R_{\mathrm{r}\sigma})$ is the dimensionless conductance of the junction r and $\Delta\mu_{\mathrm{r}\sigma} = \mu_{\mathrm{r}} - \mu_\sigma$, with μ_{r} denoting the electrochemical potential of the r-th electrode. Here $\alpha^\pm(\epsilon) = \sum_{\mathrm{r}\sigma} \alpha^\pm_{\mathrm{r},\sigma}(\epsilon)$ and $\alpha(\epsilon) = \alpha^+(\epsilon) + \alpha^-(\epsilon)$, whereas the probability $p^{(0)}_n$ obeys the equation $p^{(0)}_n \alpha^+(\Delta_n) - p^{(0)}_{n+1}\alpha^-(\Delta_n) = 0$ with $\sum_n p^{(0)}_n = 1$. The second order (cotunneling) contribution to electric current can be divided into four parts, $I^{(2)} = \sum_{i=1}^4 I^{(2)}_i$,

[1] Corresponding author. E-mail: martinek@ifmpan.poznan.pl

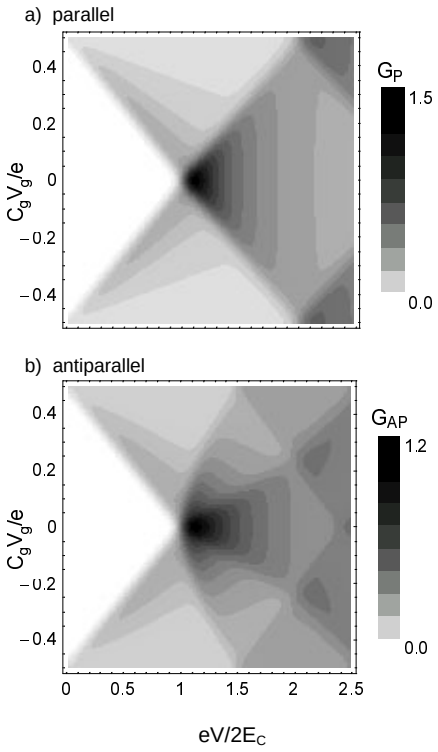

Fig. 1. The differential conductance [multiply by $(R_{\rm R}+R_{\rm L})$] versus gate $V_{\rm g}$ and transport V voltages in a gray-scale representation in the (a) parallel and (b) antiparallel configurations calculated for Co electrodes in sequential tunneling limit ($a \gg 1$).

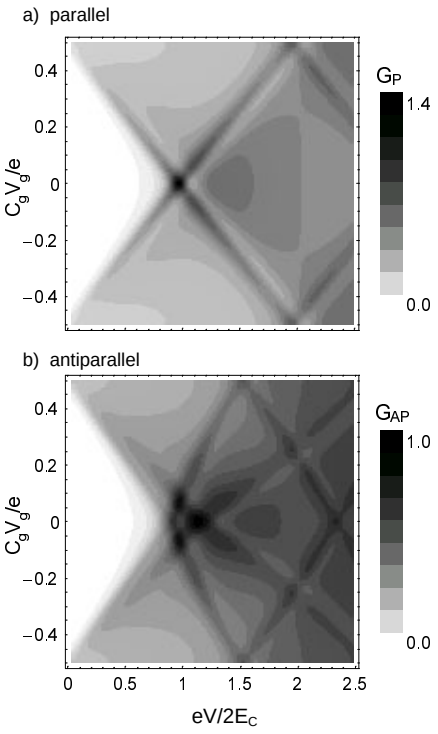

Fig. 2. The differential conductance (the units as in Fig. 1) versus gate $V_{\rm g}$ and transport V voltages calculated for Co electrodes in cotunneling limit ($a = 5$).

with $I_i^{(2)} = \sum_\sigma I_{i{\rm L}\sigma}^{(2)} = -\sum_\sigma I_{i{\rm R}\sigma}^{(2)}$. The four terms describe respectively the processes in which one electron enters and other one leaves the island coherently, the renormalization of the tunneling conductance, the renormalization of the energy gap, and processes in which two electrons enter or leave the island coherently [4,5]. The spin accumulation on the island can be determined from the spin balance equation, with the spin relaxation term taken generally into account, $\sum_{\rm r}(I_{{\rm r}\sigma}^{(1)} + I_{{\rm r}\sigma}^{(2)}) - e\mu_\sigma D_{\rm I}/\tau_{\rm sf} = 0$, where $\tau_{\rm sf}$ is the spin relaxation time and $D_{\rm I}$ is the density of states on the island.

Numerical calculations were performed for both parallel (P) and antiparallel (AP) alignment of the electrode magnetization. For the parallel alignment $R_{\rm R\uparrow} = R_{\rm L\uparrow} = aR_{\rm Q}$ and $R_{\rm R\downarrow} = R_{\rm L\downarrow} = (1-P)/(1+P)R_{\rm R\uparrow}$, where $R_{\rm Q} = h/e^2$, P is the spin polarization of the electrodes (0.35 for Co). For the antiparallel alignment one then finds $R_{\rm R\uparrow} = R_{\rm L\downarrow} = aR_{\rm Q}$, $R_{\rm R\downarrow} = R_{\rm L\uparrow} = (1-P)/(1+P)R_{\rm R\uparrow}$.

In Fig. 1 and 2 we show the differential conductance for Co electrodes versus gate $V_{\rm g}$ and transport V voltages in a gray-scale representation for both P and AP magnetic configurations in the sequential tunneling ($a >> 1$) and cotunneling ($a = 1$) limits, calculated for $T/E_{\rm C} = 0.03$ and for no spin-flip processes. Here, $E_{\rm C} = e^2/2C$ denotes the charging energy. We find well resolved splitting of the conductance peak in the AP configuration, which is a result of the spin splitting of the corresponding electrochemical potential of the island. The main difference between both limits comes from the fact that in the sequential tunneling limit there is no current in the Coulomb blockade regime, so there is no spin accumulation and consequently no splitting of the first current step. The possibility of the observation of resonance splitting is related to the the fact that the electrochemical potential is effectively shifted by the Coulomb energy [5].

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