A Single-Spin Switch

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With magnetic tunnel junctions scaling down, new phenomena due to the correlated charge transport are anticipated. One relevant phenomenon is associated to the non-avoidable traps in the insulator. In particular, the Coulomb interaction leads to a strong repulsion on a trap, a Coulomb blockade, while the Pauli blockade results in spin-dependent correlations at the transport through quantum dots and traps [1,2]. Spin-dependent hopping is responsible for large magnetoresistance in ferromagnet-insulator-metal structures [3] and magnetic tunnel junctions, due to the strong dependence of the trap occupation \( n \) and the current on the average spin \( s \) of the trap, which are determined by the solution of the system:

\[
\frac{d}{dt} n = \Gamma_S (1 - n) - \Gamma_D n - \Gamma_D p_D S, \quad \frac{d}{dt} S = p_S \Gamma_S (1 - n) - \Gamma_D S - p_D \Gamma_D n + [s \times \omega_L]
\]

Here \( \omega_L \) is the Larmor frequency vector pointing along the magnetic field \( B \), \( \Gamma_{S,D} \) and \( p_{S,D} \) are the tunneling rates and the degrees to which the electron spins are polarized along the corresponding magnetization direction in the source and drain electrodes, respectively.

Since the spin on the trap is a vector quantity, it results in unusual correlations in multi-terminal devices. Here we analyze a three-terminal device in the configuration shown in Fig.1, where the source (1), the gate (2), and the drain (3) are ferromagnets, each described by the corresponding spin polarization \( p_i \) (\( i = 1,2,3 \)). The potential at the trap is determined by the gate voltage \( V_{GS} \), the drain-source voltage \( V_{DS} \), and the capacitances \( C_i \) (\( i=1,2,3 \)), which are assumed equal. The current \( I_\alpha \) from an electrode \( \alpha=G(Gate), S(Source), \) or \( D(Drain) \) to the trap is defined positive, if it flows from the electrode to the trap. The current continuity \( I_G + I_S + I_D = 0 \) is thus automatically ensured. In our investigations a constant gate voltage \( V_{GS} \) is applied. For \( V_{DS} < V_{GS}/2 \) the junctions “source-trap” and “trap-drain” are biased in opposite direction. Then, in single-electron transistor (SET) configuration (\( \Gamma_2 = 0, p_1 = 0 \)) the drain current is zero (Fig.2), while the current “drain-trap” \( I_D \) is negative at \( V_{DS} < V_{GS}/2 \), if all \( \Gamma_i = \Gamma \) and \( p_2=0 \), for any value of \( p_1, p_3 \) (Fig.2). The ferromagnetic gate (\( p_2=0.99 \)) suppresses \( I_D \) and \( I_G \) at \( V_{DS} < V_{GS}/2 \), however, a large \( I_G \) comparable to \( I_D \) is obtained (Fig.3, Fig.4), unless the source is also ferromagnetic (\( p_1=0.99 \)) (Fig.5). The value of \( I_D \) is further boosted, if all \( p_i=0.99 \) (Fig.6). We note that, although the behavior in Fig.6 is similar to that of a SET (Fig.2), the switching is due to the spin correlations and spin blockade alone.

Fig. 1: Schematic illustration of the device. Electron transport is caused by spin-dependent hopping between the ferromagnetic contacts.

Fig. 2: Gate and drain currents, when the gate is non-ferromagnetic ($p_2=0$). The SET drain current is also shown.

Fig. 3: The drain and gate currents are suppressed, if the trap-drain junction is backward biased and the gate is ferromagnetic ($p_2=0.99$). The gate current is nonzero for $V_{DS}>V_{GS}/2$.

Fig. 4: The currents are similar to those in Fig. 3, when, in addition to the gate, the drain is ferromagnetic ($p_2=p_3=0.99$).

Fig. 5: The gate current is suppressed, when the source and the gate are ferromagnetic ($p_1=p_2=0.99$).

Fig. 6: The drain current is the largest, while the gate current is suppressed, when all electrodes are ferromagnetic ($p_1=p_2=p_3=0.99$) in the configuration shown in Fig. 1.