Spin-dependent trap-assisted tunneling: A path towards a single spin switch

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Spin correlations during hopping transport are responsible for large magnetoluminescence effects observed at room temperature in organic light-emitting diodes [1]. Spin correlations are also believed to be the cause of the large tunnel magnetoresistance observed in trap-assisted tunneling through an oxide between normal and ferromagnetic electrodes [2, 3]. The reason for the correlations is the spin-selective escape rate from a trap to another trap or to the ferromagnetic contact. The spin-selective escape rate leads to a non-zero average spin on the trap, which affects the trap occupation and thus the current. Surprisingly, although the same transport mechanism was assumed in [2] and [3], the magnetoresistance dependences on the external magnetic field direction obtained in [2] and [3] were astonishingly different.

To describe spin-dependent tunneling, a generalization of the approach usually adopted for hopping is needed to incorporate the dependences of spin-selective transition rates on the magnetic field and the magnetization direction of the electrodes. The trap occupation and the spin on the trap can be determined from the stationary solution of a balance equation.

As in the case of spin-independent hopping, the balance equation can be solved numerically by a Monte-Carlo technique. In doing so, the corresponding transition rates must be determined. To identify the corresponding spin-dependent transition rates in and out of the trap, the tunneling process is considered as a two-step event consisting of the tunneling into a trap followed by the escape from the trap. Double-occupancy of the trap is prohibited by the strong Coulomb repulsion. The escape rates are obtained from the time-dependent decay of a given initial trap occupation. Because of the spin-induced correlations, the time-dependent trap occupation and the spin must be found from a 4×4 matrix differential equation. The escape rates are determined by the eigenvalues of the corresponding 4×4 relaxation matrix. In the case when the magnetic field is aligned with the magnetization in the ferromagnetic contact, the spin-dependent tunneling rates are determined by the two spin-up and spin-down eigenvalues of the relaxation matrix. In the general case, all four eigenvalues contribute to the transition rates, which explains the discrepancy between [2] and [3].

Knowing the rates in the spin-sensitive case enables the evaluation of the current as well as the low-frequency current fluctuations. We calculated the shot noise due to spin-dependent hopping and demonstrated that, due to the Pauli spin blockade, the Fano factor is significantly enhanced above its direct tunneling value [4], especially when the magnetic field is parallel to the magnetization of the ferromagnetic contacts. The shot noise enhancement may serve as an additional characteristic to determine whether the spin-dependent trap-assisted tunneling [2, 3] is the sole reason for a large magnetoresistance signal in magnetic tunnel structures.

Being a vector quantity, the non-zero spin on the trap leads to unusual correlations in multi-terminal devices. We discuss how the spin-dependent trap-assisted tunneling between the ferromagnetic source, gate and drain in a three-terminal configuration results in a single-spin switch with characteristics similar to that of a single-electron transistor.

1. Y. Wang *et al.*, *Phys. Rev. X* **6**, 011011 (2016).
2. Y. Song and H. Dery, *Phys. Rev. Lett.* **113**, 047205 (2014).
3. Z. Yue *et al.*, *Phys. Rev. B* **91**, 195316 (2015).
4. V. Sverdlov *et al.*, *Proc. 25th Intern. Symp. Nanostruct. Phys. Technol.*, St. Petersburg (2017), p. 132.