Spin-dependent Trap-assisted Tunneling Including Spin Relaxation at Room Temperature

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In order to realize spin-driven devices in semiconductors, efficient spin injection and detection must be possible. Two schemes to analyze spin injection into a semiconductor are available [1]. A signal obtained with the three-terminal scheme at room temperature was documented for both n- and p-doped silicon in 2009 [2]. Electric signals believed to be corresponding to spin injection through silicon dioxide at 500K have also been reported [3]. However, the discrepancy between the signal measured and the theoretical value [1] is several orders of magnitude. It turns out that the signal is stronger in three-terminal measurements, while it is weaker in the non-local scheme. The reasons for these discrepancies are heavily debated [4]–[7]. Recently, the large amplitude of the signal observed in the three-terminal injection method was attributed to resonant tunneling through deep impurities [4]. The large contribution to the magnetoresistance is due to a spin blockade at trap-assisted tunneling. The spin at a trap has an equal probability for being parallel or anti-parallel to the magnetization of the ferromagnetic contact. When being anti-parallel, it cannot escape to the ferromagnet and blocks the current flow from the semiconductor to the ferromagnet. The blockade is lifted, when an external magnetic field orthogonal to the magnetization is applied. The coherent spin precession in such a field was only considered in [4].

Here we include spin decoherence and spin relaxation described by the times T_2 and T_1. At room temperature and weak field these times are expected to be almost equal [8], while typically $T_2<T_1$. We solve the equations for the density matrix describing the spin dynamics including dephasing and relaxation. The trap coupling is described by the rate Γ_N of tunneling from a semiconductor and the rate Γ_F of tunneling to a ferromagnet. The current I for spin injection due to tunneling via a trap, with the spin quantization axis forming an angle Θ with the magnetization direction, is:

$$I = \frac{\Gamma_F(\Theta)\,\Gamma_N}{\Gamma_F(\Theta)+\Gamma_N}\ ,$$

where

$$\Gamma_F(\Theta) = \Gamma_F\left(1 - p^2\,\Gamma_F T_1\left\{\frac{\cos^2\Theta}{\Gamma_F T_1+1} + \frac{T_2}{T_1}\frac{\sin^2\Theta(\,\Gamma_F T_2+1)}{\omega_c^2 T_2^2+(\,\Gamma_F T_2+1)^2}\right\}\right).$$

Here ω_c is the cyclotron frequency and p is the interface current polarization. In the case $T_1 = T_2 \to \infty$ the corresponding expression in [4] is recovered. The obtained expression allows to investigate the dependence of the current on temperature through the temperature dependences of spin dephasing and relaxation as well as of the tunneling rates.

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