Spin-dependent Trap-assisted Tunneling in Ferromagnet-Oxide-Semiconductor Structures

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Silicon is an ideal material for spintronic applications due to its weak spin-orbit interaction and long spin lifetime [1,2]. Spin injection from a ferromagnetic electrode into n-type silicon was claimed at room [3] and elevated [4] temperatures. However, the amplitude of the spin-accumulation signal extracted from a three-terminal injection method [2,3] is orders of magnitude higher than predicted [1]. The reasons for this discrepancy are currently heavily debated [1,5-8]. Recently an alternative interpretation of the three-terminal signal based on spin-dependent magnetoresistance due to trap-assisted resonant tunneling was proposed [5]. However, the effects due to finite spin lifetime [6] were not taken into consideration. Here we investigate in detail the role of spin relaxation and decoherence on a trap in determining the trap-assisted tunneling magnetoresistance.

To elucidate the role of spin relaxation and decoherence we introduce the corresponding relaxation terms into a Lindblad equation for the density matrix evolution of spin on a trap. This results in coupled master equations for the density matrix elements in the presence of the spin lifetime $T_1$ and decoherence time $T_2$ ($T_2 \leq T_1$) and the tunneling rates $\Gamma_N$ from silicon and $\Gamma_\pm = \Gamma_F (1-p)$ to the ferromagnet (Fig.1). The current $I$ due to tunneling via a trap is different from $I_0 = \Gamma_F \Gamma_N / (\Gamma_F + \Gamma_N)$ and depends on the angle $\Theta$ between the spin quantization axis and the magnetization orientation.

$$I = e \frac{\Gamma_F(\Theta) \Gamma_N \Gamma_F(\Theta) + \Gamma_H^2}{\Gamma_F(\Theta) + \Gamma_H^2},$$

$$\Gamma_F(\Theta) = \Gamma_F \left( 1 - p^2 \frac{\Gamma_F T_1}{\Gamma_T T_1 + 1} + \frac{T_2}{T_1} \frac{\sin^2(\Theta \Gamma_F T_2 + 1)}{\omega_T^2 T_2 + (\gamma_F T_2 + 1)^2} \right).$$

(1)

$\omega_T$ is the Larmor frequency and $p$ is the ferromagnetic interface current polarization. In the case $T_1 = T_2 \to \infty$ the corresponding expression in [5] is recovered. In complement to [5], when $\Gamma_F T_1 = \Gamma_F T_2 \ll 1$, the resistance dependence on the magnetic field is of a Lorentzian shape with the half-width determined by the inverse spin lifetime. A short spin relaxation time suppresses the “spin blockade” [5] at small $\Theta$ (Fig.2) in a similar fashion as the reduction of spin polarization $p$ (Fig.3). Countercintuitively, due to a suppression of the last term in (1) at fixed $T_1$, the amplitude of the $I(\Theta)$ modulation becomes larger for shorter $T_2$ (Fig.4). In contrast to [5], at finite $T_1$ the modulation of $I(\Theta)$ is present at any trap position relative to the contacts (Fig.5). Finally, an unusual non-monotonic dependence with $T_2$ of the magnetoresistance half-width as a function of the perpendicular magnetic field $B$, with the linewidth decreasing, at shorter $T_2$ is shown in Fig.6.

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Fig. 1: The trap is connected to electrodes with the rates $\Gamma_N$ and $\Gamma_\pm$. A magnetic field $B$ defines the trap spin quantization axis OZ' at an angle $\Theta$ to the magnetization orientation OZ in the ferromagnet.

Fig. 2: Current in units of $e\Gamma_N$ as a function of $\Theta$ for $p=1$, $\Gamma_N/\Gamma_F = 10$, $\omega_L/\Gamma_F = 1$, $\Gamma_F T_1 = 10$, and several values of $T_2/T_1$.

Fig. 3: Current as a function of $\Theta$, for $\Gamma_N/\Gamma_F = 10$, $\omega_L/\Gamma_F = 1$, $\Gamma_f T_1 = \Gamma_f T_2 = 10$, and several values of $p$.

Fig. 4: Current as a function of $\Theta$, for $p=1$, $\Gamma_N/\Gamma_F = 10$, $\omega_L/\Gamma_F = 1$, $\Gamma_f T_1 = 10$, and several values of $T_2/T_1$.

Fig. 5: Normalized current as a function of the position $x$ relative to silicon, for $p=1$, $\Gamma_N=\Gamma_F exp(-x/d)$, $\Gamma_f=\Gamma_0 exp(-d-x)/d)$, $T_2=T_1$, $\omega_L T_2 = \Gamma_0 T_2 = 10$.

Fig. 6: Magnetoresistance signal as a function of the perpendicular magnetic field $B$ for several $T_2/T_1$, for $p=0.8$ and $\Gamma_f T_1 = 10$. The field $B_0$ is parallel to the magnetization in the ferromagnet.