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

Viktor Sverdlov and Siegfried Selberherr

Institute for Microelectronics, TU Wien, Gußhausstraße 27-29, 1040 Vienna, Austria
e-mail: {Sverdlov|Selberherr}@iue.tuwien.ac.at

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 Γ_N from silicon and $\Gamma_\pm = \Gamma_F(1\text{-}p)$ 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 Θ between the spin quantization axis and the magnetization orientation.

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

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

ω_L 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 Θ (Fig.2) in a similar fashion as the reduction of spin polarization p (Fig.3). Counterintuitively, 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.

This work is supported by the European Research Council through the grant #247056 MOSILSPIN.

[1] R.Jansen, *Nature Mater.* **11**, 400 (2012)
[2] V.Sverdlov, S.Selberherr, *Phys.Rep.* **585,**1 (2015)
[3] S.P.Dash *et al.*, *Nature*, **462**, 491 (2009)
[4] C.Li *et al.*, *Nature Commun.* **2**,245 (2011)
[5] Y.Song, H.Dery, *PRL* **113**, 047205 (2014)
[6] V.Sverdlov, S.Selberherr, *SpinTec,*114 (2015)
[7] A.Spiesser *et al.*, *PR*B ***90***, 205213 (2014)
[8] K.-R.Jeon *et al.*, *PR*B, **91**, 155305 (2015)

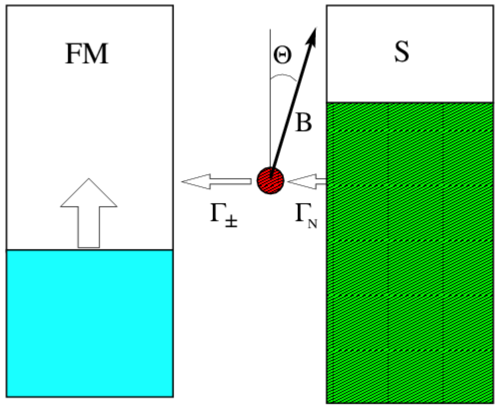

Fig.1: *The trap is connected to electrodes with the rates Γ_N and $\Gamma_\pm$. A magnetic field* ***B*** *defines the trap spin quantization axis OZ' at an angle Θ to the magnetization orientation OZ in the ferromagnet.*

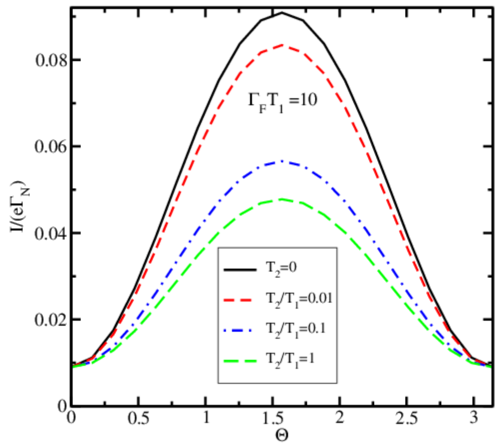

Fig.4: *Current as a function of Θ, for p=1, Γ_N/Γ_F = 10, ω_L/Γ_F = 1, $\Gamma_F T_1$ = 10, and several values of T_2/T_1.*

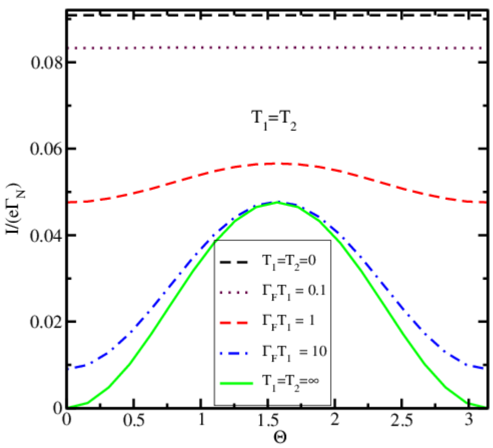

Fig.2: *Current in units of $e\Gamma_N$ as a function of Θ for p=1 Γ_N/Γ_F = 10, ω_L/Γ_F = 1, and several values of T_2=T_1.*

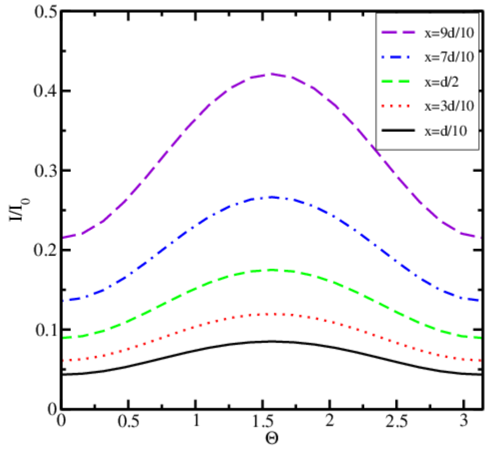

Fig.5 *Normalized current as a function of the position x relative to silicon, for p=1, Γ_N=Γ_0 exp(-x/d) , Γ_F=Γ_0 exp(-(d-x)/d), T_2=T_1, $\omega_L T_2$ = $\Gamma_0 T_2$ =10,*

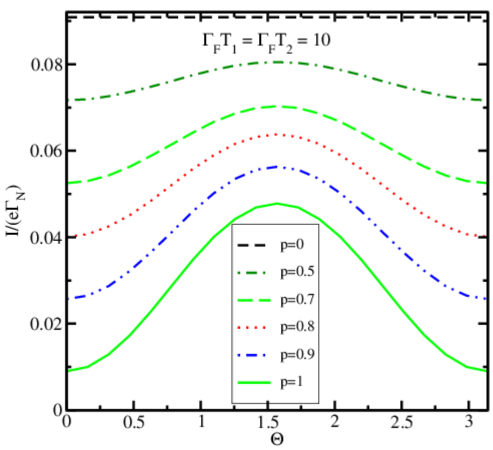

Fig.3: *Current as a function of Θ, for Γ_N/Γ_F = 10, ω_L/Γ_F = 1, $\Gamma_F T_1$ = $\Gamma_F T_1$ = 10, and several values of p.*

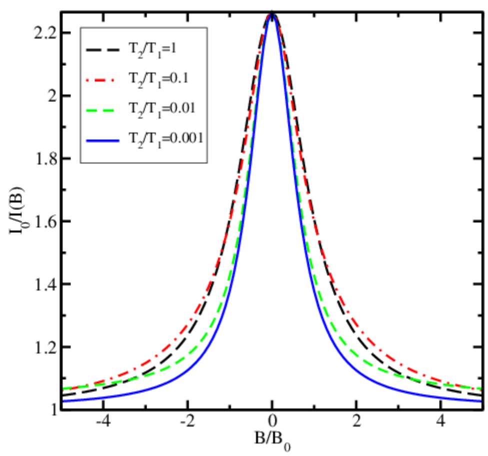

Fig.6: *Magnetoresistance signal as a function of the perpendicular magnetic field* ***B*** *for several T_2/T_1, for p=0.8 and $\Gamma_F T_1$ = 10. The field* ***B_0*** *is parallel to the magnetization in the ferromagnet.*