Spin-dependent Resonant Tunneling in Ferromagnet-Oxide-Silicon Structures

Viktor Sverdlov and Siegfried Selberherr
Institute for Microelectronics, TU Wien, Gußhausstraße 27-29, A-1040 Wien, Austria
Email: {Sverdlov|Selberherr}@iue.tuwien.ac.at

1. Introduction

Silicon, the main material of microelectronics, is perfectly suited for spin-driven applications due to its weak spin-orbit interaction and long spin lifetime [1,2]. Spin injection from a ferromagnetic electrode into *n*-silicon was claimed at room temperature [3] and also at elevated temperatures [4]. However, the amplitude of the signal extracted from a three-terminal injection method [3,4] is orders of magnitude larger than that predicted by a theory [1], provided the signal is caused by spin accumulation in silicon. Possible reasons for this discrepancy are currently heavily debated [1,5-8]. An alternative interpretation of the three-terminal signal magnitude based on spin-dependent magnetoresistance due to trap-assisted resonant tunneling was proposed [5]; however, the effects of spin dynamics and spin relaxation [6], which are important at room temperature, were not taken properly into consideration. Our goal has been to investigate the role of the spin dynamics on a trap including spin relaxation and decoherence in order to determine the trap-assisted tunneling magneto-resistance.

2. Method and Results

To highlight 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.

$$\rho = \alpha I + a\sigma_x' + b\sigma_y' + c\sigma_z' \qquad (1)$$

Here *a,b,c* are the spin projection expectation values on the axes *x',y',z'*, with the *z'* axis along the direction of the local magnetic field on the trap. The tunneling rate Γ_N from silicon to a trap does not depend on spin, while the tunneling rate $\Gamma_\pm = \Gamma_F(1 \pm p)$ from the trap to a ferromagnet depends on the spin projection $\sigma = \pm$ on the magnetization direction; here $p \leq 1$ is the interfacial current polarization in the ferromagnet. Assuming the local magnetic field on the trap is tilted by an angle Θ with respect to the magnetization (Fig.1), the following system of coupled stationary equations for the density matrix coefficients is obtained:

$$b\omega_L + c\left(\frac{1}{T_2} + \Gamma_F\right) = 0 \qquad (2)$$

$$c\,\omega_L \cos(\Theta) - a\sin(\Theta)\left(\frac{1}{T_1} + \Gamma_F\right) - b\cos(\Theta)\left(\frac{1}{T_2} + \Gamma_F\right) = 0 \qquad (3)$$

$$b\sin(\Theta)\left(\frac{1}{T_2} + \Gamma_F\right) - a\cos(\Theta)\left(\frac{1}{T_1} + \Gamma_F\right) - c\,\omega_L \sin(\Theta) = p\Gamma_F\alpha \qquad (4)$$

$$(\Gamma_F + \Gamma_N)\alpha + p\Gamma_F(a\cos(\Theta) - b\sin(\Theta)) = \Gamma_N \qquad (5)$$

Here ω_L is the spin precession Larmor frequency. The master equations include the spin lifetime T_1 and coherence time T_2 (typically $T_2 \leq T_1$). The current *I* due to tunneling via a trap is computed as

$$I = e\,\Gamma_F(1 - \alpha). \qquad (6)$$

The current *I* differs 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. Solving equations (2-6) results in the following expressions:

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

$$\Gamma_F(\Theta) = \Gamma_F\left(1 - p^2\,\Gamma_F T_1\left\{\frac{\cos^2\Theta}{\Gamma_F T_1 + 1} + \frac{T_2}{T_1}\frac{\sin^2\Theta(\Gamma_F T_2 + 1)}{\omega_L^2 T_2^2 + (\Gamma_F T_2 + 1)^2}\right\}\right) \qquad (6)$$

In the case $T_1 = T_2 \to \infty$ one obtains

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

which is the corresponding expression for *I* from [5].

In extension to [5], (7) includes the effects of spin relaxation. When $\Gamma_F T_1 = \Gamma_F T_2 \ll 1$, the resistance dependence on the magnetic field is a Lorentzian function with the half-width determined by the inverse spin lifetime. A short spin relaxation time suppresses the "spin blockade" [5], which appeared at small Θ (Fig.2), in a similar fashion as the reduction of spin current polarization *p* (Fig.3). Due to the suppression of the last term in (6) at short T_2 with T_1 fixed, the amplitude of the $I(\Theta)$ modulation with Θ becomes more pronounced (Fig.4), in contrast to the intuitive expectation that strong decoherence should reduce the effect. In contrast to [5], at finite T_1 the modulation of $I(\Theta)$ is present at an arbitrary 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.

References

[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., PRB 90, 205213 (2014)
[8] K.-R.Jeon et al., PRB, 91, 155305 (2015)

This work is supported by the ERC grant #247056 MOSILSPIN.

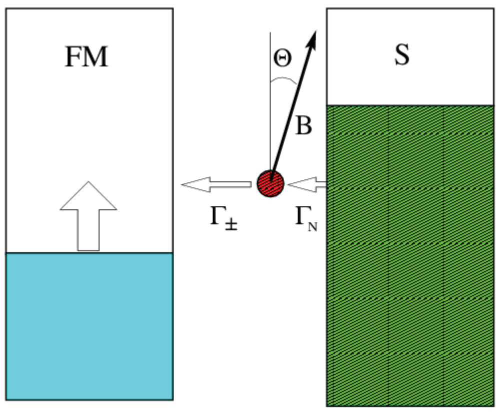

Fig.1: *An electron tunnels with the rate Γ_N on the trap and $\Gamma_\pm$ to the ferromagnet. A magnetic field* ***B*** *defines the trap spin quantization axis OZ', which is at an angle Θ to the magnetization orientation OZ in the ferromagnetic contact.*

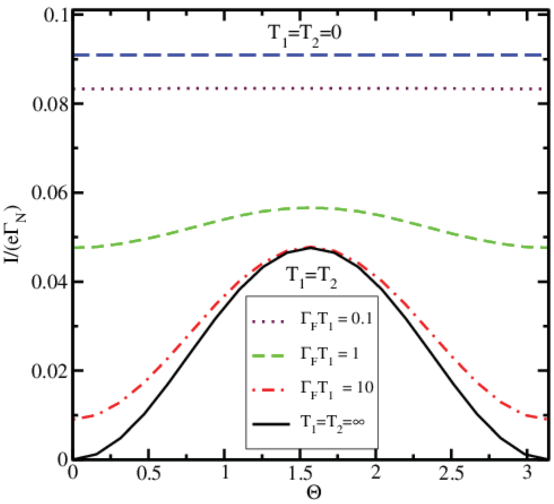

Fig.2: *Current in units of $e\Gamma_N$ as a function of Θ for p=1 Γ_N/Γ_F = 10, ω_L/Γ_F = 1, and several values of T_2=T_1.*

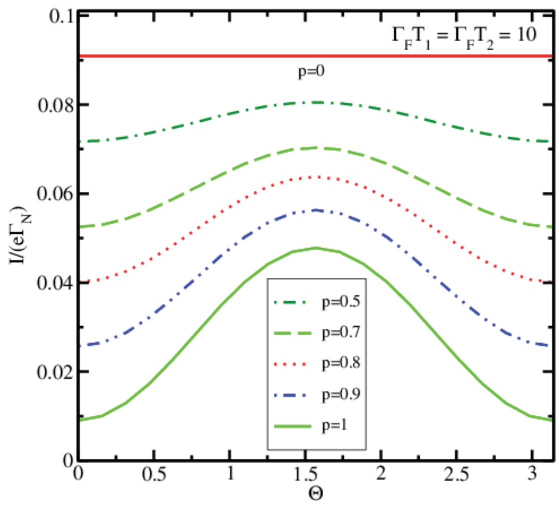

Fig.3: *Current as a function of Θ, for Γ_N/Γ_F = 10, ω_L/Γ_F = 1, $\Gamma_F T_1$ = $\Gamma_F T_1$ = 10, and several values of p.*

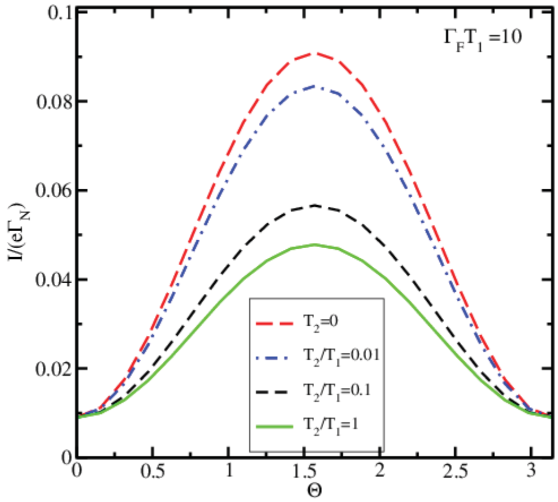

Fig.4: *Current as a function of Θ, for p=1, Γ_N/Γ_F = 10, ω_L/Γ_F = 1, $\Gamma_F T_1$ = 10, and several values of T_2/T_1.*

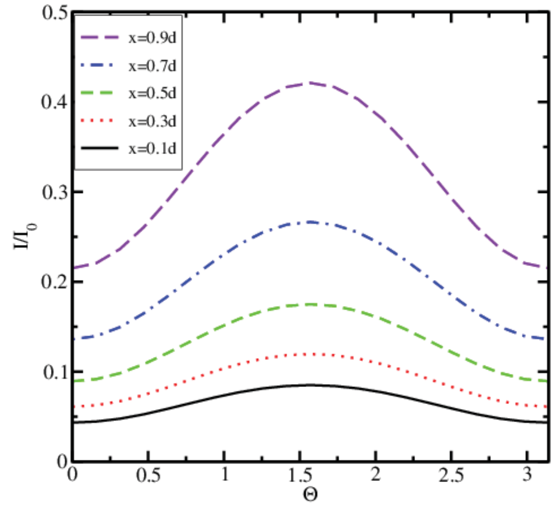

Fig.5: *Normalized current as a function of the position x, for p=1, Γ_N=Γ_0 exp(-x/d), Γ_F=Γ_0 exp(-(d-x)/d),T_2=T_1, $\omega_L T_2$ = $\Gamma_0 T_2$ =10*

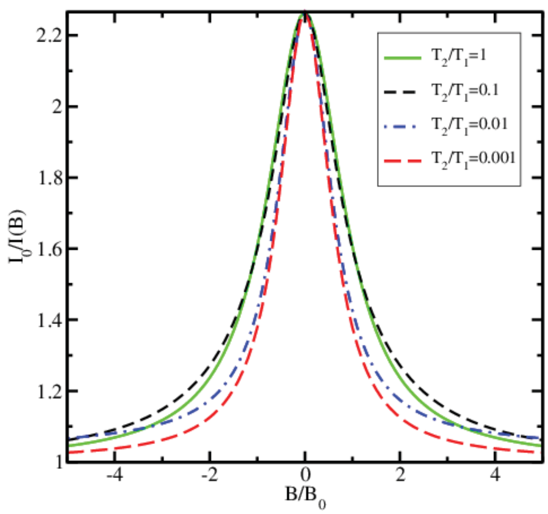

Fig.6: *Magnetoresistance signal as a function of the perpendicular magnetic field* ***B*** *for several T_2/T_1, for p=0.8 and $\Gamma_F T_1$=10. The field* ***B_0*** *is parallel to the magnetization in the ferromagnet.*