Current in Magnetic Tunnel Junctions at Spin-Dependent Hopping

Viktor Sverdlov[1], Josef Weinbub[2], and Siegfried Selberherr[1]

[1] *Institute for Microelectronics, TU Wien, Gußhausstr. 27-29, 1040 Wien, Austria*
[2] *Christian Doppler Laboratory for High Performance TCAD, Institute for Microelectronics, TU Wien, Gußhausstr. 27-29, 1040 Wien, Austria*
e-mail: Selberherr@TUWien.ac.at

Spin correlations at *hopping* are responsible for large effects observed at room temperature in organic light-emitting diodes [1] and also for the large tunnel magnetoresistance (TMR) observed in trap-assisted resonant tunneling between the normal and the ferromagnetic electrode through an oxide [2,3]. The reason for the correlations is the spin-selective escape rate from a trap into the ferromagnet resulting in a non-zero average spin at the trap. The trap occupation n (and thus the current), however, depends on the spin $\mathbf{s}=(s_x, s_y, s_z)$, which can be determined from the stationary solution of the balance matrix equation generalized to describe spin-dependent hopping in a magnetic tunnel junction (MTJ) sketched in Fig.1.

$$\frac{d}{dt}\begin{pmatrix} n \\ s_x \\ s_y \\ s_z \end{pmatrix} = \Gamma_N(1-n)\begin{pmatrix} 1 \\ \mathrm{p}_2 \sin\zeta\cos\varphi \\ \mathrm{p}_2 \sin\zeta\sin\varphi \\ \mathrm{p}_2\cos\zeta \end{pmatrix} - \mathrm{A}\begin{pmatrix} n \\ s_x \\ s_y \\ s_z \end{pmatrix},$$

$$\mathrm{A} = \begin{pmatrix} \Gamma_\mathrm{F} & |\mathbf{p}|\Gamma_\mathrm{F}\sin(\Theta) & 0 & |\mathbf{p}|\Gamma_\mathrm{F}|\cos(\Theta) \\ |\mathbf{p}|\Gamma_\mathrm{F}\sin(\Theta) & \Gamma_\mathrm{F}+1/T_2 & \omega_\mathrm{L} & 0 \\ 0 & -\omega_\mathrm{L} & \Gamma_\mathrm{F}+1/T_2 & 0 \\ |\mathbf{p}|\Gamma_\mathrm{F}\cos(\Theta) & 0 & 0 & \Gamma_\mathrm{F}+1/T_1 \end{pmatrix} \qquad (1)$$

Electrons tunnel from the right ferromagnetic contact with the rate Γ_N to the trap, from which they escape with the rate Γ_F to the left ferromagnetic contact. The contacts are characterized by the spin polarizations $\mathbf{p}_2$ and $\mathbf{p}$, to which the electron spins are aligned with the corresponding magnetization directions defined by the polar and azimuthal angles (ζ, φ) and $(\Theta,0)$ relative to the direction of the magnetic field, respectively. $T_{1,2}$ are the spin relaxation times on the trap, and ω_L is the Larmor frequency.

The stationary solution of (1) for the occupation allows to obtain the current $I=e\Gamma_N(1\text{-}n)$:

$$I = e\frac{\Gamma_F(\Theta)\,\Gamma_N}{\Gamma_F(\Theta)+\Gamma_2(\Theta,\zeta,\varphi)} \qquad (2a)$$

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

$$\Gamma_2(\Theta,\zeta,\varphi) = \Gamma_N\left(1 - pp_2\,\Gamma_F T_1\left\{\frac{\cos\Theta\cos\zeta}{\Gamma_F T_1+1} + \frac{T_2}{T_1}\frac{\sin\Theta\sin\zeta(\Gamma_F T_2+1)}{\omega_L^2 T_2^2+(\Gamma_F T_2+1)^2}\left(\cos\varphi - \frac{\omega_L T_2}{\Gamma_F T_2+1}\sin\varphi\right)\right\}\right) \qquad (2c)$$

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Fig. 2 shows the dependence of current as a function of Θ for several values of ζ, for φ = 0 (both magnetizatons are in the same plane, Fig.1), Γ_N=10Γ_F, ω_L=Γ_F, p=p_2=0.9, without spin relaxation. The current has a maximum at Θ = ζ, when the contact magnetizations are parallel. In addition, there is a smaller current increase at Θ = -ζ. The second maximum value is found to increase with the magnetic field, when the spin precession is faster. Because the spin precesses within the cone passing through both magnetizations, the rise of the magnetic field and the frequency of precession increases the chance of an electron to escape.

A high magnetic field suppresses the terms with *sinus* functions (2). The terms can also be suppressed by dephasing (T_2=0), which results in the current being symmetric with respect to Θ = ±ζ as shown in Fig.3. Unexpectedly, the stronger dephasing results in a larger current modulation (cf. Fig. 2). Even more surprising, the TMR due to spin-dependent hopping (r≈12) is larger than that of the MTJ (r≈8.5). A 40% TMR boost is important for the improved functionality of MTJs, in particular as a large TMR is paramount for modern MTJ-based MRAM.

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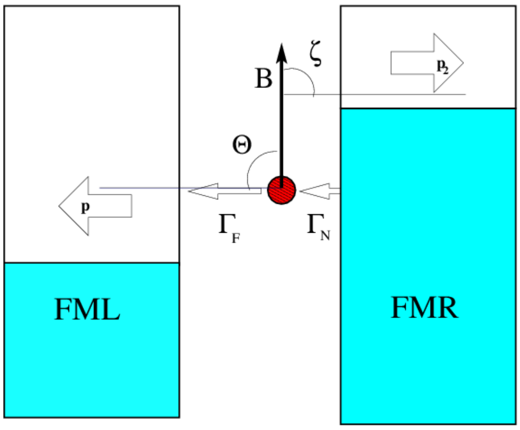

Fig.1 Schematic illustration of the system studied.

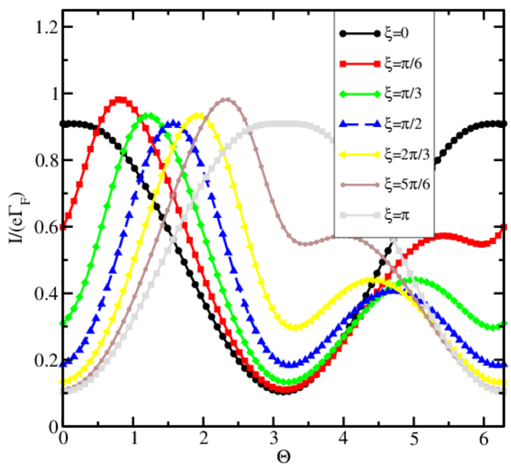

Fig.2 Spin-dependent trap-assisted tunneling without spin relaxation for Γ_N=10Γ_F, ω_L=Γ_F, p=p_2=0.9, φ = 0.

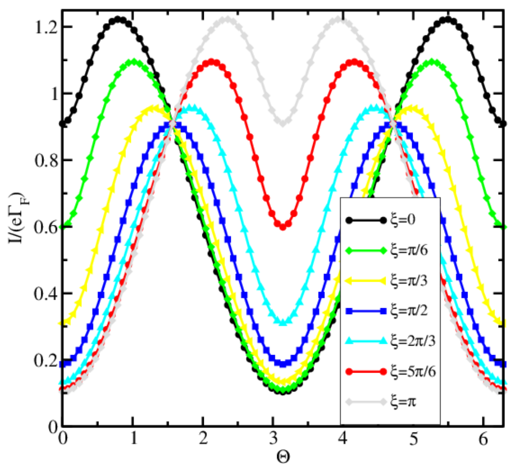

Fig.3 Same as in Fig.2 with strong spin dephasing. TMR at spin-dependent hopping is enhanced as compared to the MTJ's TMR.

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