Current and Shot Noise at Spin-dependent Hopping in Magnetic Tunnel Junctions

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Abstract— **Upcoming mass production of energy efficient spin-transfer torque magnetoresistive random access memory (MRAM) will revolutionize modern microelectronics by introducing non-volatility not only for memory but also for logic [1]. However, the pressing issue is to boost the sensing margin by improving the tunneling magnetoresistance ratio (TMR). We demonstrate that spin-dependent trap-assisted tunneling in magnetic tunnel junctions (MTJs) can increase the TMR. The influence of spin decoherence and relaxation on the current and shot noise at trap-assisted hopping is investigated.**

Keywords-Spin-dependent hopping, shot noise, spin relaxation, MTJ, MRAM

Spins injected from a nonmagnetic semiconductor on a trap are oriented in arbitrary direction with equal probability. In case the spin is parallel to the magnetization of the ferromagnetic electrode with the polarization p, its escape rate to the ferromagnet is enhanced by a factor (1+p), while it is decreased by a factor (1-p) for the antiparallel orientation. In the later case, the electron is locked on the trap for a longer time. At the same time the electron blocks another electron from entering the trap (the Coulomb blockade). Thus, due to spin correlations the current is reduced as compared to trap-assisted tunneling between the normal electrodes.

Spin decoherence described by the time T_2 is effectively equivalent to the strong magnetic field [2], see Fig.1. Spin relaxation (T_1) reduces spin correlations and the magnetoresistance modulation (Fig.1). The current and the spectral function of the current fluctuations at low frequency $S(\omega=0)$ and the Fano-factor $F(\omega=0)=S/2eI$ are calculated by a Monte Carlo technique [3], with escape rates from the trap determined by the matrix equation:

$$\frac{d}{dt}\begin{pmatrix} n \\ s_x \\ s_y \\ s_z \end{pmatrix} = -\mathrm{A}\begin{pmatrix} n \\ s_x \\ s_y \\ s_z \end{pmatrix},$$

$$\mathrm{A} = \begin{pmatrix} \Gamma_F & p\Gamma_F \sin\Theta & 0 & \Gamma_F \cos\Theta \\ p\Gamma_F \sin\Theta & \Gamma_F + 1/T_2 & \omega_L & 0 \\ 0 & -\omega_L & \Gamma_F + 1/T_2 & 0 \\ p\Gamma_F \cos\Theta & 0 & 0 & \Gamma_F + 1/T_1 \end{pmatrix} \quad (1)$$

Θ is the angle between the magnetic field and the magnetization, ω_L is the Larmor frequency. Fig.2 shows that the noise is enhanced above the single-electron limit (F=1) due to spin correlations. Spin dephasing reduces the noise to below the single-electron limit, when the magnetic field is perpendicular to the magnetization. Spin relaxation suppresses spin correlations everywhere and brings the noise to the spin-independent value.

In an MTJ the second electrode is a ferromagnet with the magnetization along the direction determined by the angles (ζ, φ) relative to the magnetic field ($\varphi = 0$ in the following) and the polarization p_2. The current and the noise are evaluated with the help of (1) complemented with the initial condition that the trap is occupied by an electron (n=1) with a non-zero average spin determined by the injection from the source ferromagnet:

$$\begin{pmatrix} n \\ s_x \\ s_y \\ s_z \end{pmatrix}(t=0) = \begin{pmatrix} 1 \\ p_2 \sin\zeta \cos\varphi \\ p_2 \sin\zeta \sin\varphi \\ p_2 \cos\zeta \end{pmatrix} \quad (2)$$

Fig.3 shows the dependence of the current as a function of Θ for several values of ζ, $\Gamma_N=10\Gamma_F$, $\omega_L=\Gamma_F/2$, $p=p_2=0.8$. The current has a maximum at $\Theta = \zeta$, where the contact magnetizations are parallel. The noise shown in Fig.4 is enhanced around $\Theta \approx \zeta \approx 0$, when the current is large. This appears to be in contradiction to Fig.2, where the noise has a maximum at the minimum of the current. However, the noise enhancement in both cases is due to spin correlations.

For the drain magnetization parallel to the magnetic field (Θ =0) the transport is determined by the two channels with the rates $\Gamma_F(1 \pm p)$. The probability to excite the channels is proportional to the injection rates $\Gamma_N(1 \pm p_2)$ for $\zeta \approx 0$. The time-dependent charge transfer process is represented by the bursts of high currents through the fast channel, separated by long periods with low current through the slow channel. As the probability to excite the fast channel is largest at ζ =0, the current is maximal. At the same time, the charge transferred during the current bursts between the two periods of low currents is maximal, which determines the high value of the shot noise in the high current state of MTJs.

Fig.5 shows the effect of spin dephasing and relaxation on the charge current due to trap-assisted tunneling through an MTJ, for ζ =0. As in Fig.1, the difference between the maximum and the minimum currents is enhanced at strong dephasing. Importantly, the TMR at spin-dependent hopping with strong dephasing is larger than the TMR at direct tunneling [4], indicating the potential of spin-dependent hopping for MTJs' transport properties optimizations.

Fig.6 displays the influence of spin dephasing and relaxation on the low frequency noise for ζ =0. Spin relaxation suppresses spin correlations and brings the noise to the level of spin-independent hopping. Spin dephasing shifts the current maximum to finite Θ, where the noise is significantly suppressed as compared to its highest value at $\Theta = 0$. In conclusion, strong spin dephasing at spin-dependent hopping enhances the TMR, while simultaneously reducing the noise level.

REFERENCES

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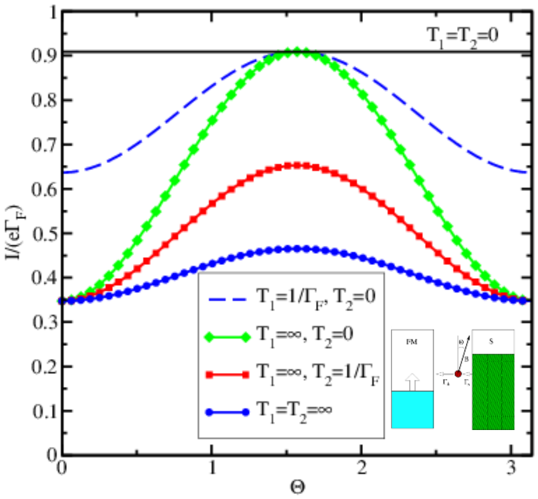

Fig.1. Current between the normal and ferromagnetic electrodes due to trap-assisted hopping (Inset) as a function of the angle Θ between the magnetic field and the magnetization. The parameters are described in the caption of Fig.2.

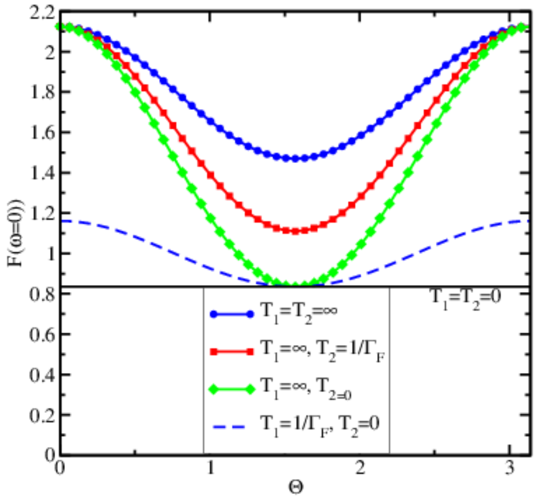

Fig.2. The Fano factor $F=S/2eI$ characterizing the low frequency current noise as a function of Θ, for several values of the spin decoherence time T_2 and relaxation time T_1. The parameters (Fig.1, Fig.2) are: $\Gamma_N=10\Gamma_F$, $\omega_L=\Gamma_F/2$, p=0.8.

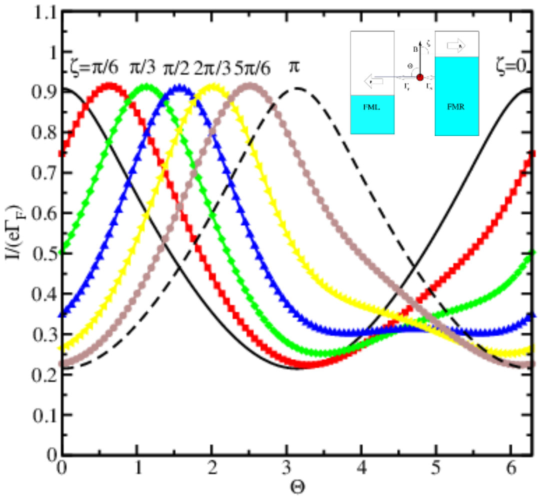

Fig.3. Spin-dependent trap-assisted current through an MTJ (Inset) as a function of the angle Θ, for several values of the angle ζ between the magnetic field and the source magnetization. The same parameters as in Fig.4.

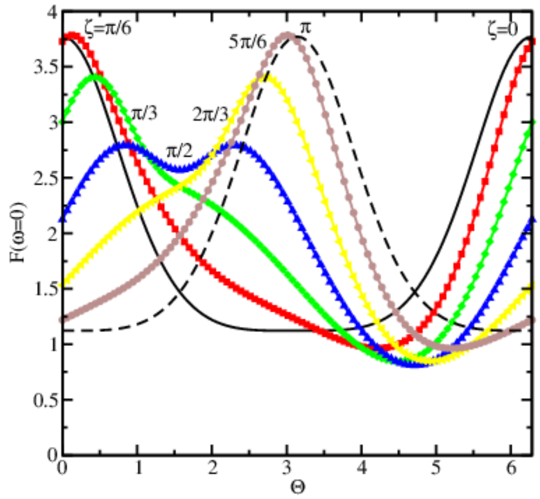

Fig.4. The Fano factor at spin-dependent hopping in an MTJ. The parameters (Fig.3-Fig.6) are: $\Gamma_N=10\Gamma_F$, $\omega_L=\Gamma_F/2$, $p=p_2$=0.8. It is assumed that there is no spin relaxation nor dephasing in Fig.3, Fig.4.

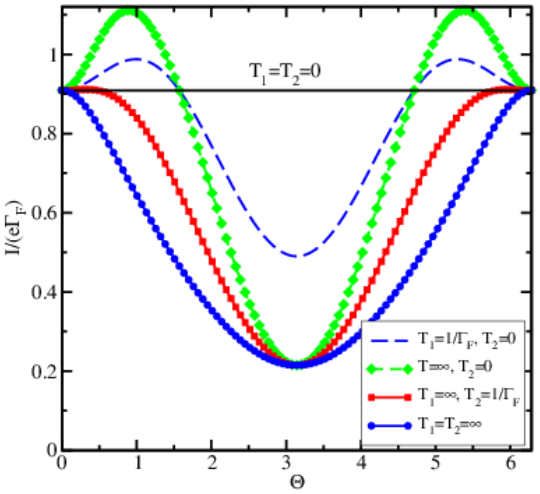

Fig.5. Influence of dephasing/relaxation on the current in Fig.4 for $\zeta = 0$ (the source magnetization is along the field).

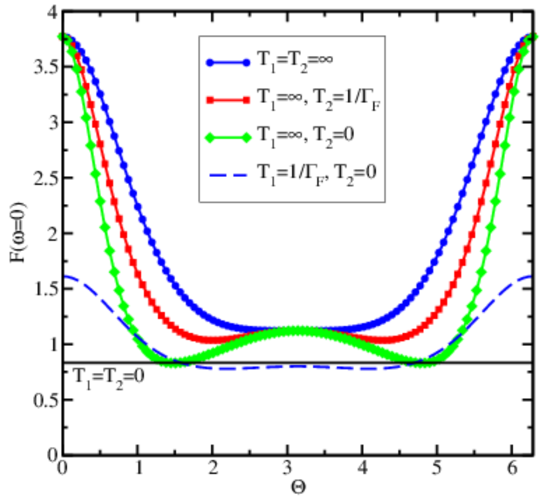

Fig.6. The Fano factor for parameters in Fig.5. Strong dephasing boosts the TMR and suppresses the noise.