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

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***Abstract*—Upcoming mass production of energy efficient spin-transfer torque magnetoresistive random access memory will revolutionize modern microelectronics by introducing non-volatility not only for memory but also for logic. However, the pressing issue is to boost the sensing margin by improving the tunneling magnetoresistance ratio. We demonstrate that spin-dependent trap-assisted tunneling in magnetic tunnel junctions 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

I. INTRODUCTION

Fabrication 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]. Boosting the sensing margin by improving the tunneling magnetoresistance ratio (TMR) is an important challenge currently under intense investigation. With reducing dimensions of magnetic tunnel junctions (MTJs) many interesting phenomena due to correlated spin-charge transport appear.

The Coulomb interaction leads to the repulsion of the charges on a trap. The repulsion leads to the Coulomb blockade which results in strong charge transport correlations. Indeed, when electrons tunnel through a trap [2], a second electron from a metallic contact cannot enter the trap, if it is already occupied by an electron. However, when the electron is released from the trap to a contact, the Coulomb repulsion does not prevent a second electron entering the trap. The electron transport is a sequence consisting of an electron hopping from the source electrode to the trap followed by the electron escaping the trap to the drain electrode. Because the Coulomb repulsion is a purely classical interaction, electron tunneling through a trap represents an example of classically correlated charge transport.

The Pauli exclusion principle forbidding two electrons with the same spin orientation to occupy the same trap quantum state results in yet another correlation affecting the transport through quantum dots [3] and traps. Spin correlations were recently found to be responsible for large magnetoresistance and magnetoluminescence effects observed at room temperature in organic semiconductors and organic light-emitting diodes [4].

Spin-dependent resonant tunneling is also believed to be responsible for the large resistance modulation [5] in a magnetic field observed in three-terminal spin accumulation experiments [6-9], with a different expression for the magnetoresistance dependence of the magnetic field derived in [10]. To describe spin-independent hopping in normal metal/oxide/ferromagnet structures and to resolve the controversy, we have recently generalized the transition rates to/from a trap by incorporating the electron spin [11]. Therewith the stationary current and its low-frequency fluctuations can be evaluated by a Monte Carlo algorithm [11-13]. Here, we investigate the current and the low-frequency current fluctuations described by the shot noise in ferromagnet/oxide/ferromagnet structures, or MTJs.

II. METHOD

In contrast to spin-independent tunneling, the transition rates with spin depend on the magnetic field and the magnetization direction of the electrodes. In the case when an electron jumps from the ferromagnetic source electrode to the trap with the rate $\Gamma_N^+(\Gamma_N^-)$ and from the trap to the ferromagnetic drain electrode with the rates $\Gamma_F^+(\Gamma_F^-)$ for the spin parallel (anti-parallel) to the magnetization $\mathbf{M}_N$ and $\mathbf{M}_F$, respectively (Figure1), the trap occupation $0<n<1$ depends on the average electron spin **s** at the trap as it is described by (1).

$$\frac{d}{dt}n = 2\Gamma_N(1-n) - \Gamma_F n - \Gamma_F \mathbf{p_2 s} \qquad (1a)$$

$$\frac{d}{dt}\mathbf{s} = 2\mathbf{p_2}\Gamma_N(1-n) - \Gamma_F\mathbf{s} - \mathbf{p}\Gamma_F n + [\mathbf{s}\times\boldsymbol{\omega}_L] \qquad (1b)$$

Here $\boldsymbol{\omega}_L = \frac{e\mathbf{B}}{mc}$ is the Larmor frequency pointing along the external field **B**, $\mathbf{p}_{2()} = \frac{\Gamma_{N(F)}^+ - \Gamma_{N(F)}^-}{2\Gamma_{N(F)}}\frac{\mathbf{M}_{N(F)}}{M_{N(F)}}$ is the interface spin current polarization in the source (drain) ferromagnetic electrode with the saturation magnetization $M_{S(D)}$, and $\Gamma_{N,F} = \frac{\Gamma_{N,F}^+ + \Gamma_{N,F}^-}{2}$. In order to determine the escape probability $P_2(t)$= 1 - $n(t)$ from the trap it is convenient to rewrite the equations (1) in a matrix form.

$$\frac{d}{dt}\begin{pmatrix} n \\ s_x \\ s_y \\ s_z \end{pmatrix} = 2\Gamma_N(1-n)\begin{pmatrix} 1 \\ p_2 \sin\zeta\cos\varphi \\ p_2\sin\zeta\sin\varphi \\ p_2\cos\zeta \end{pmatrix} - \mathbf{A}\begin{pmatrix} n \\ s_x \\ s_y \\ s_z \end{pmatrix}, \qquad (2a)$$

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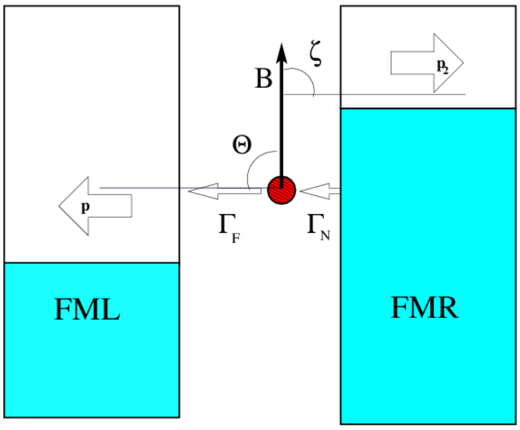

Fig. 1. Trap-assited tunneling between the source and drain ferromagnetic electrodes. The magnetizations along the polarizations **p**$_2$, **p** are non-colinear and form angles Θ, ζ with respect to the magnetic field **B**. (It is shown for simplicity that **p**$_2$, **p** and **B** are lying within the same plane: φ=0).

$$\mathbf{A} = \begin{pmatrix} \Gamma_F & p\Gamma_F\sin(\Theta) & 0 & p\Gamma_F\cos(\Theta) \\ p\Gamma_F\sin(\Theta) & \Gamma_F + 1/T_2 & \omega_L & 0 \\ 0 & -\omega_L & \Gamma_F + 1/T_2 & 0 \\ p\Gamma_F\cos(\Theta) & 0 & 0 & \Gamma_F + 1/T_1 \end{pmatrix}. \quad (2b)$$

In addition to (1) the phenomenological spin relaxation time T_1 and the spin dephasing time T_2 are introduced in (2) to take these processes into account, which depend on the dynamics of the spin projections on the axes in the coordinate system **s**=(s_x, s_y, s_z) with the OZ axis parallel to the magnetic field **B**. Θ is the angle between the magnetic field and the drain magnetization and the angles (ζ, φ) define the orientation of the source magnetization relative to the magnetic field **B** (Figure 1).

The escape rates from the trap are determined by solving the time-dependent equation (2a) with $\Gamma_N = 0$ for $n(t)$ [13]. The initial condition for the time-dependent equation is defined by the source electrode, namely, that at the initial moment the trap is occupied ($n(t=0) = 1$) with the initial spin $\mathbf{s}(t=0) = \mathbf{p}_2$.

$$\frac{d}{dt}\begin{pmatrix} n \\ s_x \\ s_y \\ s_z \end{pmatrix} = -A\begin{pmatrix} n \\ s_x \\ s_y \\ s_z \end{pmatrix} \quad (3a)$$

$$\begin{pmatrix} n \\ s_x \\ s_y \\ s_z \end{pmatrix}(t=0) = \begin{pmatrix} 1 \\ p_2\sin\zeta\cos\varphi \\ p_2\sin\zeta\sin\varphi \\ p_2\cos\zeta \end{pmatrix} \quad (3b)$$

The tunneling rate from the ferromagnetic drain to the trap does not depend on its polarization and is just the sum of the tunneling rates with the spin-up and the spin-down projections on the axis oriented along the drain polarization $\mathbf{p}_2$.

$$\Gamma_{S\rightarrow Trap} = \Gamma_N^+ + \Gamma_N^- = 2\Gamma_N \quad (4)$$

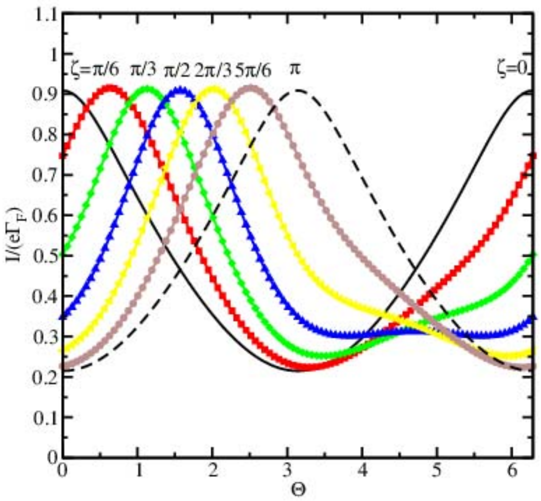

Fig. 2. Trap-assited tunneling current between the source and drain ferromagnetic electrode as a function of Θ for several ζ. The parameters are: $\Gamma_N=5\Gamma_F$, $\omega_L=\Gamma_F/2$, $p=p_2=0.8$. It is assumed that there is no spin relaxation nor dephasing.

With the spin-dependent tunneling rates determined, the calculation of the current and the shot noise is straightforward by using a Monte Carlo technique [13]. Before doing this, we evaluate the expression for the tunneling current analytically in the next section.

III. CALCULATING THE CURRENT

The current I through a trap due to spin-dependent trap-assisted hopping can be alternatively found from the stationary solution from (2) for the average trap occupation n as [14]

$$I = 2e\Gamma_N(1-n), \quad (5a)$$

$$I = e\frac{2\,\Gamma_F(\Theta)\,\Gamma_N}{\Gamma_F(\Theta) + \Gamma_2(\Theta,\zeta,\varphi)}, \quad (5b)$$

$$\Gamma_F(\Theta) = \Gamma_F\left(1 - p^2\,\Gamma_F T_1\left\{\frac{\cos^2\Theta}{\Gamma_F T_1 + 1} + \frac{T_2}{T_1}\frac{\sin^2\Theta(\Gamma_F T_2 + 1)}{\omega_L^2 T_2^2 + (\Gamma_F T_2 + 1)^2}\right\}\right), \quad (5c)$$

$$\Gamma_2(\Theta,\zeta,\varphi) = 2\Gamma_N\left(1 - p_2 p\,\Gamma_F T_1\left\{\frac{\cos\Theta\cos\zeta}{\Gamma_F T_1 + 1} + \frac{T_2}{T_1}\frac{\sin\Theta\sin\zeta(\Gamma_F T_2 + 1)}{\omega_L^2 T_2^2 + (\Gamma_F T_2 + 1)^2}\left(\cos\varphi - \frac{\omega_L T_2}{\Gamma_F T_2 + 1}\sin\varphi\right)\right\}\right), \quad (5d)$$

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 with **B**, Fig.1), $\Gamma_N=5\Gamma_F$, $\omega_L=\Gamma_F/2$, $p_2 = p = 0.8$, 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 is

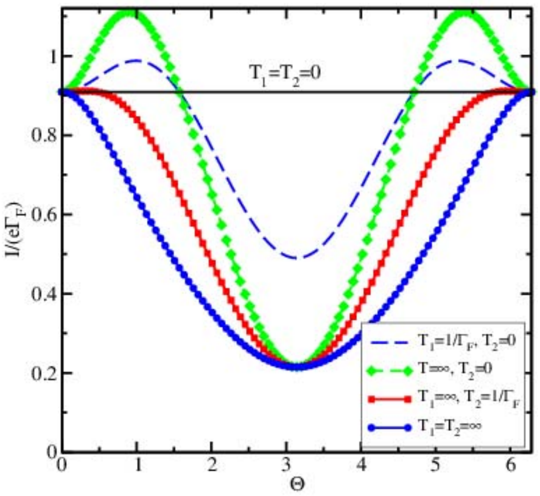

Fig. 3. Trap-assisted tunneling current between the source and the drain ferromagnetic electrode as a function of Θ for several ζ. The parameters are $\Gamma_N=5\Gamma_F$, $\omega_L=\Gamma_F/2$, $p=p_2=0.8$. It is assumed that there is no spin relaxation

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 increase 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). Fig.3 shows the effect of spin dephasing and relaxation on the charge current due to trap-assisted tunneling through an MTJ, for ζ=0. The difference between the maximal and the minimal current is enhanced at strong dephasing. One peculiarity is that the maximal current is achieved at Θ ≠ ζ as shown in Fig.3. Importantly, the TMR at spin-dependent hopping with strong dephasing is larger than the TMR at direct tunneling [14], indicating the potential of spin-dependent hopping for MTJs' transport properties optimization.

IV. SHOT NOISE CALCULATIONS

The charge transport consists of a series of repeated cycles: An electron jumps from the source electrode to the trap with the rate (4) $2\Gamma_S$, followed by the electron hop from the trap to the ferromagnetic electrode with the probability $P_2(t) = 1- n(t)$, where $n(t)$ is determined from (3). Double occupancy of the trap is prohibited by the Coulomb repulsion. One electron charge is transferred at each cycle during the time $\tau=\tau_1+\tau_2$. The fluctuation time τ_1 is evaluated by a direct Monte Carlo technique according to the distribution probability

$$P_1(\tau_1)= 1- \exp(-\tau_1/(2\Gamma_N)). \qquad (6a)$$

The time τ_2 is distributed according to

$$P_2(\tau_2) = 1-n(\tau_2), \qquad (6b)$$

and it is evaluated with the rejection technique. The total current I is computed as

$$I=\frac{eN}{\sum_{i=1}^{N}(\tau_1+\tau_2)_i}, \qquad (6c)$$

where N is a large number of cycles i.

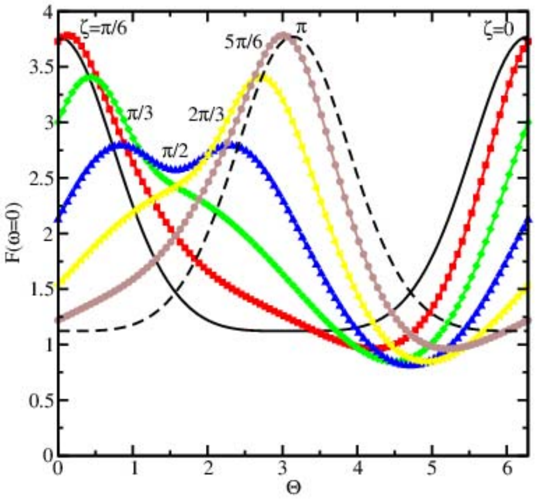

Fig. 4. Shot noise at trap-assisted tunneling between the source and the drain ferromagnetic electrode as a function of Θ for several ζ. The parameters are $\Gamma_N=5\Gamma_F$, $\omega_L=\Gamma_F/2$, $p_2=p=0.8$. It is assumed that there is no spin relaxation

We have checked that the results for current calculations obtained by simulating the charge transfer as a series of consecutive electron hops and performing the time averaging by means of the Monte Carlo technique reproduce the stationary current values in Fig.2 and Fig.3.

In order to evaluate the current fluctuations at low frequency ω we need to evaluate the current-current correlator

$$S(\omega\to 0)=2\int_{-\infty}^{\infty}(\langle I(t+x)I(t)\rangle - I^2)\cos\omega x\ dx, \qquad (7)$$

where I is the stationary current obtained by time averaging of the time dependent current $I(t)$ described by the consecutive electron hops performed with random times τ_1 and τ_2, respectively. For a series of the consecutive electron hops the correlator (7) can be evaluated by using the following expression [15]:

$$S(\omega\to 0)=2eI\left(\frac{N\sum_{i=1}^{N}(\tau_1+\tau_2)_i^2}{(\sum_{i=1}^{N}(\tau_1+\tau_2)_i)^2}-1\right) \qquad (8)$$

Fig.4 shows the shot noise normalized by the current value evaluated with (8) as a function of Θ for several values of ζ, $\Gamma_N=5\Gamma_F$, $\omega_L=\Gamma_F/2$, $p=p_2=0.8$. The Fano factor F is defined as

$$F=\frac{S(\omega\to 0)}{2eI}\quad . \qquad (9)$$

The Fano factor F shown in Fig.4 is significantly enhanced around Θ ≈ ζ ≈ 0. The enhancement is correlated with the large current values shown in Fig.2 for the same parameters. We note that this behavior is opposite to the one predicted for spin-dependent trap-assisted hopping between a normal and a ferromagnetic electrode [16], where the noise has a maximum at the current minimum. We note, that although the correlations between the current and the noise are opposite in MTJs and for transport between a metal and a ferromagnetic electrode, in both cases the noise enhancement above its single electron limit is due to spin correlations.

Indeed, at spin-independent hopping between two metal electrodes with the rate Γ_1 for an electron to jump on the trap

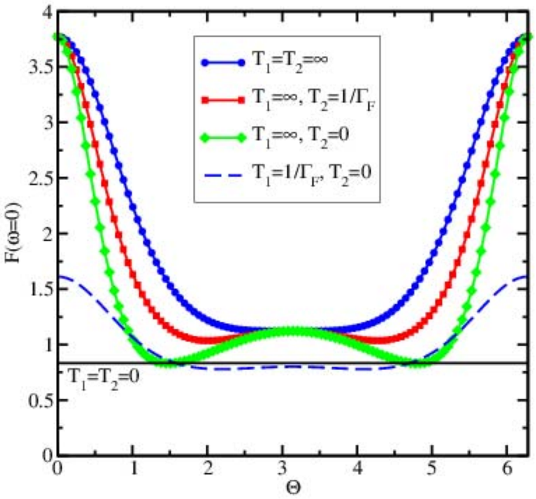

Fig. 5. Effect of spin relaxation and dephasing on shot noise at spin-dependent trap-assisted hopping between the source and the drain ferromagnetic electrode as a function of Θ for $\zeta = 0$. The parameters are Γ_N=5Γ_F, ω_L=$\Gamma_F/2$, p_2=p=0.8.

and the rate Γ_2 to escape from the trap the Fano factor is found in [15] as

$$F = \left(\frac{{\Gamma_1}^2 + {\Gamma_2}^2}{(\Gamma_1 + \Gamma_2)^2}\right) < 1. \tag{10}$$

As a consequence, at spin-uncorrelated trap-assisted hopping the Fano factor is always smaller than one corresponding to the limit of consecutive single electron transfer. Therefore, the Fano factor enhancement above one in Fig.4 is due to spin-induced correlations at transport.

In the following we explain the enhancement of the shot noise. 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 current is maximal, which determines the high value of the shot noise in the high current state of MTJs.

Fig.5 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 (10), which is below one. As follows from Fig.3, strong spin dephasing increases the differences between the minimum and the maximum values. At the same time the current maximum is shifted the to finite Θ. By inspecting Fig.5 we conclude that the noise level is significantly decreased at the current maximum, as the noise is significantly suppressed compared to its highest value at $\Theta = 0$. Thus, strong spin dephasing at spin-dependent hopping enhances the TMR, while simultaneously reducing the noise level.

V. CONCLUSION

Electron current and shot noise at trap-assisted hopping in magnetic tunnel junctions is evaluated. It is demonstrated that the spin-induced correlations play a critical role in determining the current modulation and especially the noise level. Surprisingly, spin dephasing enhances the TMR and simultaneously reduces the noise level rendering the potential of spin-dependent hopping for practical applications.

REFERENCES

[1] D. Apalkov, B. Dieny, and J.M. Slaughter, “Magnetoresistive Random Access Memory”, Proc. of the IEEE, vol. 104, pp. 1796–1830 (2016).

[2] D. V. Averin and K. K. Likharev, “Coulomb Blockade of Single-Electron Tunneling, and Coherent Oscillations in Small Tunnel Junctions”, J. Low Temp. Phys. vol.62, pp. 345-373 (1986).

[3] N K. Ono, D.G. Austing, Y. Tokura, S. Tarucha, “Current Rectification by Pauli Exclusion in a Weakly Coupled Double Quantum Dot System”, Science 297, 1313 (2002).

[4] Y. Wang, K. Sahin-Tiras, N.J. Harmon, M. Wohlgenannt, M.E. Flatté, “Immense Magnetic Response of Exciplex Light Emission due to Correlated Spin-Charge Dynamics”, Phys.Rev.X 6, 011011 (2016).

[5] Y. Song and H. Dery, “Magnetic-Field-Modulated Resonant Tunneling in Ferromagnetic-Insulator-Nonmagnetic Junctions”, Phys. Rev. Let. vol. 113, 047205 (2014).

[6] S.P. Dash, S. Sharma, R.S. Patel, M.P. de Jong, and R.Jansen “Electrical Creation of Spin Polarization in Silicon at Room Temperature”, Nature, vol.462, pp. 491-484 (2009).

[7] C.H. Li, O.M.J. van 't Erve, and B.T. Jonker “Electrical Injection and Detection of Spin Accumulation in Silicon at 500 K with Magnetic Metal/Silicon Dioxide Contacts”, Nature Communications, vol.2, art.245 (2011).

[8] R. Jansen, “Silicon Spintronics”, Nature Materials, vol.11, pp. 400-408, (2012).

[9] V. Sverdlov and S. Selberherr, “Silicon Spintronics: Advances and Challenges“, Physics Reports, vol.585, pp. 1-40 (2015).

[10] Z. Yue, M.C. Prestgard, A. Tiwari, M.E. Raikh, “Resonant Magnetotunneling between Normal and Ferromagnetic Electrodes in Relation to the Three-terminal Spin Transport”, Phys. Rev. B, vol. 91, 195316 (2015).

[11] V. Sverdlov, J. Weinbub, S. Selberherr, “Spin-Dependent Trap-Assisted Tunneling in Magnetic Tunnel Junctions: A Monte Carlo Study”; in "Abstract Book International Workshop on Computational Nanotechnology", pp.88-90 (2017).

[12] S. Bakhvalov, G.S. Kazacha, K.K. Likharev, S.I. Serdyukova, “Single-electron Solitons in One-dimensional Tunnel Structures”, Sov.Phys.JETP 68, pp. 581-587 (1989).

[13] V. Sverdlov, A. N. Korotkov, and K. K. Likharev, “Shot-Noise Suppression at Two-Dimensional Hopping”, Phys.Rev.B, vol. 63, 081302R (2001).

[14] V. Sverdlov, J. Weinbub, and S. Selberherr, “Current in Magnetic Tunnel Junctions at Spin-Dependent Hopping”, in "Abstracts Workshop on Innovative Devices and Systems (WINDS)" ISBN: 978-3-901578-31-1, pp. 87 – 88 (2017).

[15] J. Kinkhabwala and A.N. Korotkov, “Shot Noise at Hopping via Two Sites”, Phys.Rev. B vol. 62, pp. R7727-R7730 (2000).

[16] V. Sverdlov and S. Selberherr, “Current and Shot Noise at Spin-dependent Hopping in Magnetic Tunnel Junctions”, EUROSOI-ULIS 2018, accepted.