Shot Noise in Magnetic Tunnel Junctions

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ABSTRACT

Spin-transfer torque magnetoresistive random access memory will potentially revolutionize microelectronics by introducing nonvolatility not only in memory circuits but also in logic circuits. One of the pressing issues, however, is to boost the sensing margin between the two states of logic. Although spin-dependent trap-assisted tunneling in magnetic tunnel junctions can increase the tunneling magnetoresistance ratio and thus the sensing margin, current irregularities resulting in a large shot noise value may negate the advantages. Surprisingly, strong spin dephasing is shown to improve the tunneling magnetoresistance ratio, while keeping the noise level acceptable.

Keywords: Spin-dependent hopping; shot noise; spin relaxation; MTJ; MRAM

1. INTRODUCTION

Energy efficient spin-transfer torque magnetoresistive random access memory (MRAM) will restructure upcoming microelectronic circuitry by introducing nonvolatility not only for memory circuits but also for logic circuits [1]. However, increasing the sensing margin by improving the tunneling magnetoresistance ratio (TMR) is an important challenge currently under investigation. Interestingly, spin-dependent trap-assisted hopping is shown to increase the TMR over its value at direct tunneling, if the spin dephasing is strong.

In order to treat spin-dependent single electron hopping, the Coulomb interaction leading to the repulsion of the charges on a trap must be considered. The repulsion leads to the Coulomb blockade, when double occupancy of the trap is prohibited. This results in strong correlations at electron transport [2], as it is performed in sequences consisting of an electron hopping from the source electrode to the trap, followed by the electron escaping the trap to the drain electrode.

At spin-dependent hopping, the Pauli exclusion principle plays an equally important role as it forbids two electrons with the same spin projections to occupy the same trap quantum state. This results in additional correlations affecting the transport through the double-quantum dot system in a magnetic field [3]. These spin-driven correlations are responsible for large magnetoresistance and magnetoluminescence effects observed at room temperature in organic semiconductors and organic light-emitting diodes [4]. In case of ferromagnetic contacts, the electron impinging an electrode from a trap has a larger probability to be accommodated by the electrode, if its spin is parallel to the magnetization of the electrode [5]. Then the drain electrode plays a role similar to the second quantum dot in the Pauli spin blockade experiments [3]. The drain electrode-induced spin correlations result in a Pauli blockade-like trap-assisted tunneling transport between the ferromagnetic electrodes. The spin-dependent resonant tunneling is believed to be responsible for the large magnetoresistance modulation [5] observed in three-terminal spin accumulation experiments [6-10], as the non-equilibrium spin injection in silicon was reliably ruled out [11] as a source of the large signal.

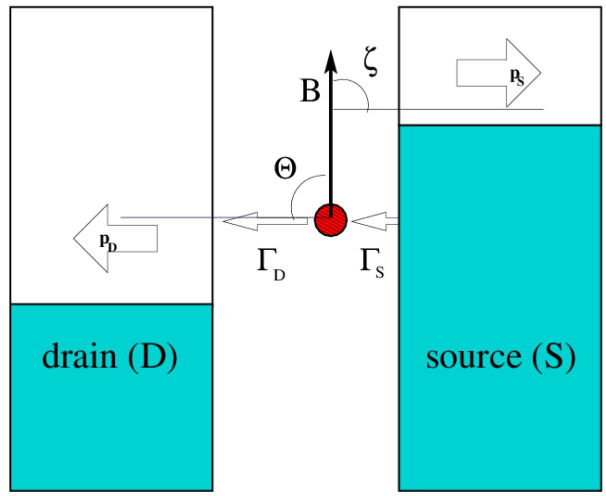

Figure 1 The ferromagnetic source (S) / drain (D) polarizations $\mathbf{p}_{S,D}$ form angles Θ and ζ, with respect to the magnetic field **B**. The trap is coupled by the rates $\Gamma_{S(D)}$ to the source (drain).

Here, we evaluate and analyze low frequency current fluctuations at spin-dependent hopping. These fluctuations are caused by peculiarities of the charge transfer by single electrons at hopping and are often referred to as shot noise. We demonstrate that the enhanced shot noise is a clear fingerprint of spin-dependent hopping in magnetic tunnel structures. Therefore, measuring the shot noise would provide an additional confirmation that the spin-dependent tunneling is the cause of the large magnetoresistance observed in three-terminal spin injection experiments. We include spin dephasing and relaxation on the trap and we demonstrate that, surprisingly, the strong spin dephasing leads to enhanced tunneling magnetoresistance, though at an unusual non-collinear relative orientation of the magnetizations in the source and drain. We also show that under these conditions the shot noise is at an acceptably low level in the presence of dephasing.

2. METHOD

To describe spin-dependent transport through a magnetic tunnel structure shown in Fig. 1, the stochastic Liouville equation for the spin density matrix ρ is typically employed. In the case of a magnetic tunnel junction with the non-magnetic source it has got the form [12]:

$$\frac{d}{dt}\rho = -\frac{i}{\hbar}[H,\rho] - \Gamma_D^{+}\{\Pi_D^{+},\rho\} - \Gamma_D^{-}\{\Pi_D^{-},\rho\} + \Gamma_S I(1-\mathrm{Tr}\rho) \quad (1)$$

[,] ({,}) is a commutator (anti-commutator), $H = \frac{\hbar}{2}\boldsymbol{\omega}_L\boldsymbol{\sigma}$ $\omega_L = |\boldsymbol{\omega}_L| = \left|\frac{e\mathbf{B}}{mc}\right|$, **B** is the magnetic field, *e* and *m* are the charge and the effective mass of an electron, and *c* is the speed of light. The external magnetic field **B** at the impurity position applied in the XZ plane is assumed to form an angle Θ with the magnetization direction in the ferromagnetic lead. $\Pi_D^{+(-)}$ is the projection operator along (against) the magnetization direction of the ferromagnetic drain electrode, $\boldsymbol{\sigma} = (\sigma_x, \sigma_y, \sigma_z)$ is the vector of the Pauli matrices $\sigma_i, i = x, y, z$, and I is the unity 2×2 matrix. The tunneling rate Γ_S to the trap does not depend on spin, therefore the tunneling times τ_1 are distributed with the probability determined solely by Γ_S:

$$p_S(\tau_1) = \Gamma_S \exp(-\Gamma_S\tau_1) \quad (2)$$

The tunneling rate from the trap to a ferromagnet depends on the spin projection σ = ± on the magnetization direction:

$$\Gamma_D^{\pm} = \Gamma_D(1 \pm p_D) \quad (3)$$

The spin current polarization at the interface of the ferromagnet $p_D \leq 1$ is defined as

$$p_D = \frac{\Gamma_D^{+} - \Gamma_D^{-}}{2\Gamma_D}. \quad (4)$$

The master equation (1) coincides with the one recently derived from the Anderson impurity model in the limit of large on-site Coulomb repulsion [6]. By introducing the trap occupation *n* and the electron spin **s**, (1) can be recast in the form [13]:

$$\frac{d}{dt}n = \Gamma_S(1-n) - \Gamma_D n - \Gamma_D \mathbf{p}_D\mathbf{s} \quad (5a)$$

$$\frac{d}{dt}\mathbf{s} = -\Gamma_D\mathbf{s} - \mathbf{p}_D\Gamma_D n + [\mathbf{s}\times\boldsymbol{\omega}_L] \quad (5b)$$

The advantage of writing (1) in the form (5) is that (5b) can now be generalized to incorporate spin relaxation and dephasing described by the spin relaxation time T_1 and the dephasing time T_2, respectively [13]:

$$\frac{d}{dt}\mathbf{s} = -\Gamma_D\mathbf{s} - \mathbf{p}_D\Gamma_D n + [\mathbf{s}\times\boldsymbol{\omega}_L] - \left(\frac{1}{T_1} - \frac{1}{T_2}\right)\frac{(\mathbf{s}\cdot\boldsymbol{\omega}_L)}{\omega_L}\frac{\boldsymbol{\omega}_L}{\omega_L} - \frac{1}{T_2}\mathbf{s} \quad (5c)$$

The hopping process described by (5) is represented by two consecutive hopping events of an electron first from the normal source electrode to the trap followed by the electron escaping from the trap to the ferromagnetic electrode. While the first event is described by the single tunneling rate Γ_S, the escape process depends on the relative orientation between the spin **s** on the trap and the magnetization **M** and is thus characterized by a matrix [14]. The transition matrix **A** can be found by evaluating the time-dependent trap occupation in the case it is only connected to the drain ferromagnetic electrode. Because of the coupling to the spin, the equation is of the form:

$$\frac{d}{dt}\begin{pmatrix} n \\ s_x \\ s_y \\ s_z \end{pmatrix} = -\mathbf{A}\begin{pmatrix} n \\ s_x \\ s_y \\ s_z \end{pmatrix} \quad (6)$$

The 4×4 relaxation matrix **A is** written in the coordinate system with the OZ axis parallel to the magnetic field **B**.

$$\mathbf{A} = \begin{pmatrix} \Gamma_D & p_D\Gamma_D\sin(\Theta) & 0 & p_D\Gamma_D\cos(\Theta) \\ p_D\Gamma_D\sin(\Theta) & \Gamma_D + \frac{1}{T_2} & \omega_L & 0 \\ 0 & -\omega_L & \Gamma_D + \frac{1}{T_2} & 0 \\ p_D\Gamma_D\cos(\Theta) & 0 & 0 & \Gamma_D + \frac{1}{T_1} \end{pmatrix} \quad (7)$$

Initially the trap is occupied, which results in the initial condition for (6) $n(t=0) = 1$. Because the trap is filled from the normal source electrode, the spin at the trap is initially zero, which results in an additional initial condition $\mathbf{s}(t=0) = 0$.

It is now straightforward to generalize the approach to incorporate the ferromagnetic source electrode with the spin polarization $\mathbf{p}_S$. In this case the additional initial condition is modified as $\mathbf{s}(t=0) = \mathbf{p}_S$ [15], where the initial spin orientation is not necessarily parallel to the magnetic field **B** or the drain magnetization $\mathbf{p}_D$.

Equations (6) and (7) allow to evaluate the missing escape probability and the distribution $p_D(\tau_2)$.of the escape times τ_2 from the trap. As the charge transfer process is represented by cyclic repetition of the two consecutive electron hops from the normal source electrode on the trap followed by the electron escape from the trap to the drain, the current is evaluated by averaging over a large number *N* of cycles of charge transfer, devided by the total time. Each hopping event is independent and happens at random times τ_1 and τ_2 determined by the respective probabilities $p_{S(D)}(\tau_{1(2)})$.

The stationary current *I* can be computed as [16]

$$I = \frac{e}{<\tau_1> + <\tau_2>}, \quad (8)$$

where the average times

$$<\tau_{1(2)}> = \int_0^\infty \tau_{1(2)}\, p_{S(D)}(\tau_{1(2)})\, d\,\tau_{1(2)} \quad (9)$$

can be evaluated by a Monte Carlo technique [17] as

$$<\tau_{1(2)}> = \frac{\sum_{i=1}^{N}(\tau_{1(2)})_i}{N}. \quad (10)$$

In order to investigate the current fluctuations at low frequency ω one needs to evaluate the current-current correlator [18].

$$S(\omega \to 0) = 2\int_{-\infty}^{\infty}(\langle I(t+x)I(t)\rangle - I^2)\cos\omega x\, dx \quad (11)$$

For a series of consecutive electron hops the correlator (11) can be evaluated by using the following expression [19]:

$$S(\omega \to 0) = 2eI\left(\frac{N\sum_{i=1}^{N}(\tau_1+\tau_2)_i^2}{\left(\sum_{i=1}^{N}(\tau_1+\tau_2)_i\right)^2} - 1\right) \quad (12)$$

The Fano factor $F = \frac{S(\omega=0)}{2eI}$ is often used as the measure of shot noise strength. In a single tunnel junction *F*=1 the current transfer consists of electron bunches where more than one is transferred by consecutive single electron hops. If $F < 1$, the charge transfer is more continuous, while if $F > 1$, the charge transfer is due to electron bunches with more than one electron in a single bunch. Following (12), we evaluate the Fano factor F in the case of spin-dependent trap-assisted hopping as:

$$F = \frac{S(\omega = 0)}{2eI} = \left(\frac{\langle (\tau_1 + \tau_2)^2 \rangle}{\langle \tau_1 + \tau_2 \rangle^2} - 1 \right) \qquad (13)$$

3. RESULTS AND DISCUSSION

Fig. 2 shows the dependence of current as a function of the angle Θ between the magnetic field **B** and the polarization of the drain electrode $\mathbf{p}_D$ for several values of the angle ζ between **B** and $\mathbf{p}_S$, when both source and drain magnetizations are in the same plane with **B** (Fig. 1), $\Gamma_S=5\Gamma_D$, $\omega_L=\Gamma_D/2$, $p_S = p_D=0.8$, without spin relaxation and dephasing. The current has a maximum at $\Theta = \zeta$, when the contact magnetizations are parallel. In addition, there is a weaker current increase at $\Theta = -\zeta$. The second maximum is found to increase with the magnetic field, when the spin precession is faster. Indeed, for $\Theta = -\zeta$, the spin at the trap precesses within the cone passing through both magnetizations. Therefore, the increase of the magnetic field and the frequency of precession boosts the probability of an electron to escape from the trap.

The Fano factor F for the ideal case without spin dephasing and relaxations shown in Fig. 3 is significantly enhanced around $\Theta \approx \zeta \approx 0$. It correlates with the large current values shown in Fig. 2 for the same parameters. The noise enhancement characterized by the Fano factor above unity is casued by spin-induced correlations at spin-dependent hopping.

Indeed, for the drain magnetization parallel to the magnetic field ($\Theta = 0$) the transport is determined by the two channels with

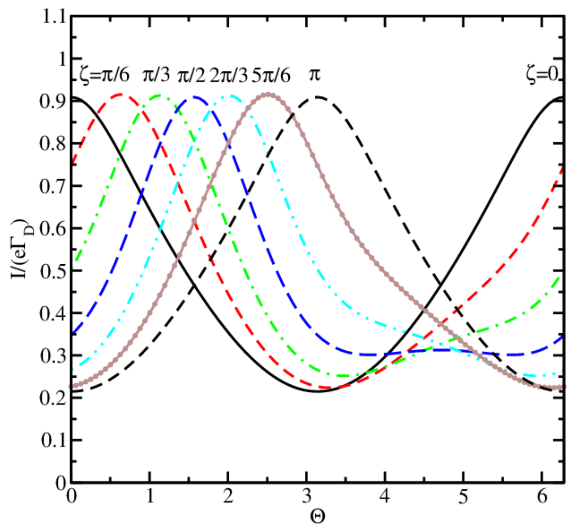

Figure 2 Trap-assisted tunneling current between ferromagnetic source and drain electrodes as a function of Θ for several ζ. The parameters are: $\Gamma_S=5\Gamma_D$, $\omega_L=\Gamma_D/2$, $p_S=p_D=0.8$. It is assumed that there is no spin relaxation nor dephasing.

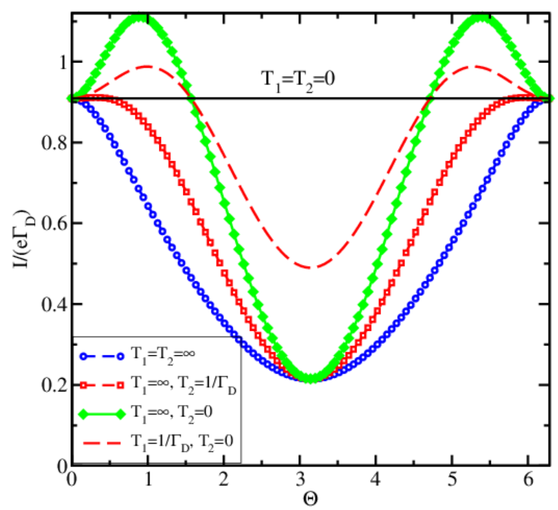

Figure 4 Trap-assisted tunneling current between ferromagnetic source and drain electrodes as a function of Θ for several ζ. The parameters are: $\Gamma_S=5\Gamma_D$, $\omega_L=\Gamma_D/2$, $p_S=p_D=0.8$. Spin dephasing is included.

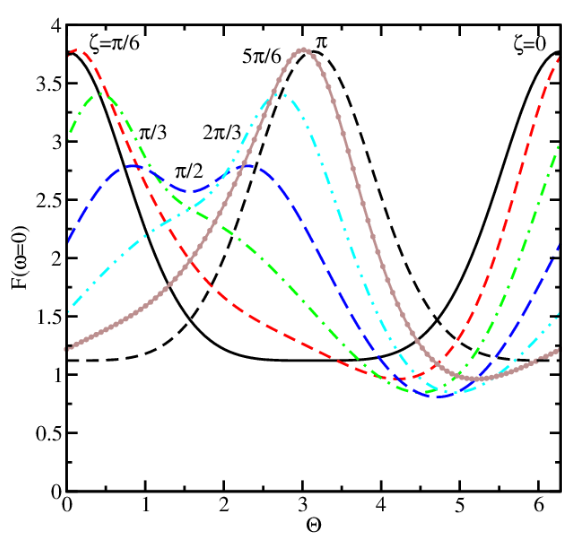

Figure 3 Fano factor at trap-assisted tunneling between ferromagnetic source and drain electrodes as a function of Θ for several ζ computed for an ideal case of no spin relaxation nor dephasing. The parameters are: $\Gamma_S=5\Gamma_D$, $\omega_L=\Gamma_D/2$, $p_S=p_D=0.8$.

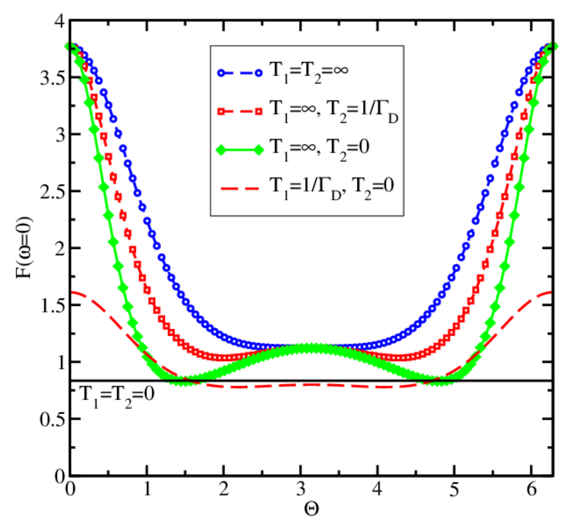

Figure 5 Effect of spin relaxation and dephasing on shot noise as a function of Θ for $\zeta = 0$. The parameters are: $\Gamma_S=5\Gamma_D$, $\omega_L=\Gamma_D/2$, $p_S=p_D=0.8$.

the rates $\Gamma_D(1 \pm p_D)$. The probability to excite the channels is proportional to the injection rates $\Gamma_S(1 \pm p_S)$ for $\zeta \approx 0$. The time-dependent charge transfer process is governed by bursts of high currents through the fast channel, when a bunch of electrons with spins parallel to the drain magnetization hops through the trap, separated by long periods with low current through the slow channel with the spin anti-parallel to the drain magnetization. As the probability to excite the fast channel is largest at $\zeta = 0$, the current is maximal. At the same time, the number of electrons 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. 4 shows the effect of spin dephasing and relaxation on the charge current due to trap-assisted tunneling through a magnetic structure, for the drain magnetization parallel to the magnetic field, ζ=0. The difference between the maximum and the minimum current is enhanced at strong dephasing. One peculiarity is that the maximal current is achieved when $\Theta \neq \zeta$ as shown in Fig. 4. Importantly, the TMR at spin-dependent hopping with strong dephasing is larger than the TMR at direct tunneling, indicating the potential of spin-dependent hopping for MTJs' transport properties optimization.

Fig. 5 displays the influence of spin dephasing and relaxation on the low frequency noise and the Fano factor for $\zeta = 0$. Spin relaxation simply suppresses spin correlations and brings the noise to the level of spin-independent hopping below unity. However, the noise suppression by spin relaxation is not interesting as it also suppresses the TMR (Fig. 4).

Strong spin dephasing, however, increases the TMR. At the same time the current maximum is shifted to finite Θ, where the shot noise is significantly suppressed as compared to its maximal value at $\Theta = 0$. Therefore strong spin dephasing at spin-dependent hopping enhances the TMR, while it simultaneously reduces the noise level.

4. CONCLUSIONS

Based on the master equation approach describing the dynamics of the electron occupation and the spin on a trap in oxide sandwiched between ferromagnetic metal contacts in presence of spin relaxation and dephasing, it is demonstrated that the spin-induced correlations play a critical role in determining the current modulation and especially the noise level.

Without spin relaxation and dephasing the shot noise and the Fano factor at spin-dependent hopping are significantly enhanced due to the Pauli spin blockade above their value at spin-independent hopping.

The role of spin dephasing on the magnetoresistance and the noise is not always detrimental. An unusual non-monotonic dependence of the magnetoresistance as a function of dephasing is predicted. Surprisingly, spin dephasing enhances the TMR and simultaneously reduces the noise level rendering the potential of spin-dependent hopping for practical applications.

5. ACKNOWLEDGMENT

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