Resistance noise in spin valves

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Fluctuations of the magnetization in spin valves are shown to cause resistance noise that strongly depends on the magnetic configuration. Assisted by the dynamic exchange interaction through the normal-metal spacer, the electrical noise level of the antiparallel configuration can exceed that of the parallel one by an order of magnitude, in agreement with recent experimental results.

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The dynamics of nanoscale spin valve pillars, in which electric currents flow perpendicular to the interface planes (CPP), attracts much interest.[1–3] The giant magnetoresistance (GMR) of such pillars of ferromagnetic films separated by normal metal makes them attractive as future read heads in magnetic hard-disk drives. However, Covington *et al.*[3] found that the performance of CPP-GMR heads might be degraded by enhanced low-frequency resistance noise. They ascribed this effect to the spin-transfer torque, i.e., the torque exerted by a spin polarized current on the magnetizations of the ferromagnetic layers.[4–6] Rebei and Simionato,[7] on the other hand, favored micromagnetic disorder as an explanation. More recently, electrical noise measurements have been carried out on CPP nanopillar multilayers with up to 15 magnetic layers.[8] Interestingly, the noise power was found to be suppressed by more than an order of magnitude by aligning the magnetizations from antiparallel to parallel in an external magnetic field.

The noise properties of small metallic structures pose challenges for theoretical physics[9] to which ferromagnetism adds a novel dimension.[10–13] The thermal fluctuations of single domain magnetic clusters have been described already 50 years ago by Brown.[10] Recently, it has been shown that by contacting a ferromagnet with a conducting environment, the magnetization fluctuations are enhanced compared to the bulk value.[13] CPP spin valves offer an opportunity to detect the enhanced magnetization noise electrically by the GMR effect, but the new degree of freedom of a fluctuating detector magnetization complicates the picture in a nontrivial way. The better understanding of the noise properties of CPP nanopillar spin valves reported in the present Brief Report should therefore be of interest for basic physics as well as for applications.

In spin valves, two sources of thermal noise must be taken into account: Direct agitation of the magnetizations due to intrinsic processes[10] and thermal spin-current fluctuations outside the ferromagnets that affect the magnetizations by means of the spin-transfer torque.[13] Here, we disregard spin-current shot noise, assuming a sufficiently small external current bias. We calculate the magnetization noise for the parallel (P) and antiparallel (AP) magnetic configurations using the stochastic equations of motion for the magnetization vectors in the macrospin model. When the relative orientation between the magnetizations fluctuates, so does, via the GMR, the electrical resistance. We show that due to static (exchange and dipolar) and dynamic (nonequilibrium spin-exchange) couplings between the ferromagnets, the resistance noise strongly depends on the magnetic configuration and applied magnetic field.

The thermal agitation of the magnetizations is conveniently described by introducing stochastic magnetic fields acting on the ferromagnets.[10,13] The fluctuations of the magnetizations, and hence the resistance noise, can then be expressed by the transverse magnetic response (susceptibility) of the magnetizations to these stochastic fields. The magnetic response of spin coherent hybrid structures depends on static and dynamic interactions between the magnetic elements, and therefore differs strongly from that of bulk systems. In spin valves, a static nonlocal exchange coupling is mediated by electrons through the normal-metal spacer, and a static dipolar coupling is caused by stray magnetic fields. Additionally, each ferromagnet couples to an external magnetic field. All these couplings affect the stability and response of the magnetic ground state, and therefore the resistance noise, by favoring either the P or AP configurations. For typical spacer thicknesses considered here and in experiments,[8] the nonlocal exchange and dipolar couplings both favor the AP configuration. Naturally, an external magnetic field favors and stabilizes the P configuration. From these simple considerations, we may expect already a dependence of the resistance noise on the magnetic configuration and applied field. The message of this Brief Report is that much more is going on, however.

The dynamic interaction in spin valves is due to *nonequilibrium* spin currents between the ferromagnets.[14,15] A ferromagnet emits spins when its magnetization changes in time ("spin pumping"),[16] which subsequently may be absorbed by the other ferromagnet as a spin-transfer torque.[14] This "dynamic exchange" couples the small-angle dynamics of the magnetizations. The coupled dynamics may be analyzed in terms of collective spin-wave-like modes[15] that govern the magnetic response, and hence the resistance noise. As we will see, the mode that governs the resistance noise in the P configuration is damped more than the respective AP mode. We show that this leads to a substantial lowering of the resistance noise level in the P configuration as compared to the AP. As discussed below, and somewhat surprisingly, this conclusion holds even though the stochastic noise fields are

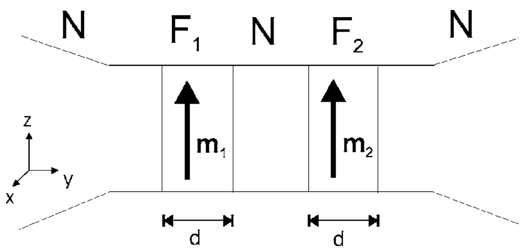

FIG. 1. A spin valve consists of two ferromagnetic thin films F_1 and F_2 separated by a normal-metal spacer N and connected to normal-metal reservoirs. The ferromagnets have magnetizations $\mathbf{m}_1$ and $\mathbf{m}_2$ (here in the parallel configuration), the same thickness d, and equal contact conductances.

stronger for the P mode than for the AP mode.

The resistance noise induced by magnetization fluctuations in spin valves is thus determined by the combined effects of the dynamic exchange coupling, static nonlocal exchange and dipolar couplings, and external magnetic field, and as a result, varies substantially with the magnetic configuration. In particular, we find that when the ferromagnets are ordered antiparallel, the noise level can be much higher than when they are parallel. Our results thus offer an explanation of the experimental findings by Covington *et al.*[8]

We consider a spin valve as pictured in Fig. 1. Two ferromagnetic films with magnetizations $\mathbf{m}_1(t)$ and $\mathbf{m}_2(t)$ (where t is the time) are separated by a thin normal-metal spacer and connected to normal-metal reservoirs. Due to thermal intrinsic and spin-current noise, the magnetizations are subject to fluctuations $\delta\mathbf{m}_1(t)=\mathbf{m}_1(t)-\langle\mathbf{m}_1\rangle$ and $\delta\mathbf{m}_2(t)=\mathbf{m}_2(t)-\langle\mathbf{m}_2\rangle$ from their time-averaged values. The ferromagnets are thicker than the magnetic coherence length so that they perfectly absorb any incoming spin current polarized transverse to the magnetization direction.[17–19] Furthermore, spin-flip processes in the middle normal metal are disregarded, which is usually allowed for CPP spin valves. The ferromagnets can then effectively communicate by means of the dynamic exchange coupling.[14,15] The static nonlocal exchange and dipolar couplings can both be described by a Heisenberg coupling $-J\mathbf{m}_1\cdot\mathbf{m}_2$, where J is the coupling strength, favoring parallel (antiparallel) alignment when $J>0$ ($J<0$). We focus on the situation in which the externally applied currents or voltages are sufficiently small to not affect the device dynamics. For simplicity, we take the spin valve to be symmetric (i.e., the two ferromagnets are identical) and consider only collinear magnetic configurations. Assuming that the static coupling J is negative, the antiparallel state is the ground state without applied external fields, while the parallel state is achieved by applying a sufficiently strong external magnetic field forcing the magnetizations to align.

The resistance noise is characterized by the correlation function

$$S(t-t')=\langle\Delta R(t)\Delta R(t')\rangle, \tag{1}$$

where $\Delta R(t)=R(t)-\langle R\rangle$. The noise is caused by fluctuations in the magnetizations via the dependence of the resistance $R(t)$ on the angle θ between the magnetizations. Close to collinear configurations, $R(t)$ can be expanded in the small fluctuations $\delta\mathbf{m}_1(t)$ and $\delta\mathbf{m}_2(t)$ as

$$R[\mathbf{m}_1(t)\cdot\mathbf{m}_2(t)]\approx R(\pm1)\mp\frac{1}{2}[\delta\mathbf{m}^{\mp}(t)]^2\left(\frac{\partial R}{\partial\cos\theta}\right)_{\mathrm{P/AP}}, \tag{2}$$

where the upper (lower) signs hold for the P (AP) orientation, $\delta\mathbf{m}^{\mp}(t)=\delta\mathbf{m}_1(t)\mp\delta\mathbf{m}_2(t)$, and the differential on the right-hand side should be evaluated for $\mathbf{m}_1\cdot\mathbf{m}_2=\cos\theta=1$ (P) or $\cos\theta=-1$ (AP). Equation (2) inserted into Eq. (1) expresses the resistance noise in terms of the magnetization fluctuations $\delta\mathbf{m}^{\mp}(t)$. Assuming that the fluctuations are Gaussian distributed,[10] we can employ Wick's theorem[20] and obtain

$$S_{\mathrm{P/AP}}(t-t')=\frac{1}{2}\left(\frac{\partial R}{\partial\cos\theta}\right)^2_{\mathrm{P/AP}}\sum_{i,j}S^2_{m_i^{\mp}m_j^{\mp}}(t-t'), \tag{3}$$

where $S_{m_i^-m_j^-}(t-t')=\langle\delta m_i^-(t)\delta m_j^-(t')\rangle$, $S_{m_i^+m_j^+}(t-t')=\langle\delta m_i^+(t)\delta m_j^+(t')\rangle$, and the summation is over all Cartesian components ($i,j=x$, y, or z). Only the difference between the magnetization vectors $\delta\mathbf{m}^-(t)$ (the antisymmetric mode) induces noise when the magnetizations are parallel, whereas only the sum $\delta\mathbf{m}^+(t)$ contributes when they are antiparallel.

The fluctuations $\delta\mathbf{m}^{\mp}(t)$ are the solutions of the stochastic Landau-Lifshitz-Gilbert (LLG) equation of motion for the magnetizations, which, when augmented to include thermal spin-current noise, dynamic exchange coupling, and static exchange and dipolar couplings, reads[15]

$$\frac{d\mathbf{m}_k}{dt}=-\mathbf{m}_k\times[\omega_0\hat{\mathbf{z}}+\omega_c(\mathbf{m}_k\cdot\hat{\mathbf{x}})\hat{\mathbf{x}}+\omega_x\mathbf{m}_l+\gamma\mathbf{h}_k(t)]$$
$$+(\alpha_0+\alpha')\mathbf{m}_k\times\frac{d\mathbf{m}_k}{dt}-\alpha'\mathbf{m}_l\times\frac{d\mathbf{m}_l}{dt}. \tag{4}$$

Here, $k,l=1,2$ denotes ferromagnets 1 or 2, $\omega_0\hat{\mathbf{z}}=\gamma\mathbf{H}_0$, where γ is the gyromagnetic ratio and $\mathbf{H}_0$ an external field applied along the z axis, $\omega_x=\gamma J/M_s d$ parametrizes the static couplings (d is the thickness of the ferromagnets and M_s the saturation magnetization), and α_0 is the intrinsic Gilbert damping constant. We have also included an in-plane anisotropy field $\omega_c(\mathbf{m}_k\cdot\hat{\mathbf{x}})\hat{\mathbf{x}}=\gamma\mathbf{H}_c$ along the x axis. $\alpha'\mathbf{m}_{1(2)}\times d\mathbf{m}_{1(2)}/dt$ is the (dimensionless) spin current emitted by ferromagnet 1 (2) (Ref. 16) that is subsequently absorbed by ferromagnet 2 (1), giving rise to the dynamic exchange coupling. The parameter $\alpha'=(\gamma\hbar\,\mathrm{Re}\,g^{\uparrow\downarrow})/(8\pi M_s\mathcal{V})$ (Ref. 15) governs the strength of the dynamic exchange coupling, where $g^{\uparrow\downarrow}$ is the dimensionless interface spin-mixing conductance (of which we have disregarded a small imaginary part),[17] and $\mathcal{V}$ is the volume of a ferromagnet. If desired, spin currents emitted to the outer normal-metal reservoirs can also be included, simply by making the substitution $\alpha_0\to\alpha_0+\alpha'$. Finally, $\mathbf{h}_k(t)$ is the effective time-dependent stochastic field representing the thermal agitation of ferromagnet k. We write $\mathbf{h}_k(t)=\mathbf{h}_k^{(0)}(t)+\mathbf{h}_k'(t)$, where $\mathbf{h}_k^{(0)}(t)$ describes the intrinsic thermal noise and $\mathbf{h}_k'(t)$ describes the (statistically independent) noise induced by spin current fluctuations via the spin-transfer torque.[13] $\mathbf{h}_k^{(0)}(t)$ has zero average and a white noise correlation function that satisfies the fluctuation-dissipation theorem[10] (FDT):

$$\langle h_{k,i}^{(0)}(t)h_{k,j}^{(0)}(t')\rangle = 2k_BT\frac{\alpha_0}{\gamma M_s\mathcal{V}}\delta_{ij}\delta(t-t'). \quad (5)$$

Here, i and j are Cartesian components and k_BT is the thermal energy.

The spin-current-induced field $\mathbf{h}_k'(t)$ can be determined using magnetoelectronic circuit theory[17] and the results of Ref. 13. Requiring conservation of charge and spin in the normal-metal spacer[11] and taking into account thermal fluctuations of the distribution function in the same spacer,[11] we arrive at the following results:[21] For collinear configurations, the spin-current-induced noise field $\mathbf{h}_k'(t)$ is given by [compare with Eq. (5)]

$$\langle h_{k,i}'(t)h_{k,j}'(t')\rangle = 2k_BT\frac{\alpha'}{\gamma M_s\mathcal{V}}\delta_{ij}\delta(t-t'). \quad (6)$$

Here, $k=1,2$, and i and j label components perpendicular to the magnetization direction. Furthermore, $\mathbf{h}_1'(t)$ and $\mathbf{h}_2'(t)$ are not statistically independent,

$$\langle h_{1,i}'(t)h_{2,i}'(t')\rangle = -\langle h_{1,i}'(t)h_{1,i}'(t')\rangle, \quad (7)$$

due to current conservation. In accordance with the FDT, the total noise field $\mathbf{h}_k(t)=\mathbf{h}_k^{(0)}(t)+\mathbf{h}_k'(t)$ is thus proportional to the total damping $\alpha=\alpha_0+\alpha'$, where α' is the enhancement of the Gilbert damping due to emission of spin currents, as defined above.

The anisotropy field and the negative exchange and/or dipolar coupling ($\omega_x<0$) align the ferromagnets antiparallel along the x axis when the external field is turned off. Then, $\mathbf{m}_k(t)\approx\pm\hat{\mathbf{x}}+\delta\mathbf{m}_k(t)$ for $k=1,2$, where $\delta\mathbf{m}_k\approx\delta m_{k,y}\hat{\mathbf{y}}+\delta m_{k,z}\hat{\mathbf{z}}$ are the transverse fluctuations induced by the stochastic noise fields. Linearizing the LLG equation in $\delta\mathbf{m}_k$, we can evaluate the magnetization noise $S_{m_i^+m_j^+}(t-t')$ using Eqs. (5)–(7), and find the resistance noise from Eq. (3). A strong external field enforces a parallel magnetic configuration. Disregarding a sufficiently weak anisotropy field in this case, $\mathbf{m}_k(t)\approx\hat{\mathbf{z}}+\delta\mathbf{m}_k(t)$, where $\delta\mathbf{m}_k\approx\delta m_{k,x}\hat{\mathbf{x}}+\delta m_{k,y}\hat{\mathbf{y}}$. This may be used to find $S_{m_i^-m_j^-}(t-t')$ and subsequently $S_P(t-t')$.

The zero-frequency resistance noise $S_{\mathrm{P/AP}}(\omega'=0)=\int d(t-t')\langle\Delta R(t)\Delta R(t')\rangle_{\mathrm{P/AP}}$ thus becomes

$$S_{\mathrm{P/AP}}(0) = \frac{2}{\pi}\left(\frac{2\gamma k_BT}{M_s\mathcal{V}}\right)^2\left(\frac{\partial R}{\partial\cos\theta}\right)^2_{\mathrm{P/AP}}\int d\omega\, X_{\mathrm{P/AP}}, \quad (8)$$

where

$$X_{\mathrm{P}} = \frac{[\omega^2+(\omega_t-\omega_c)^2]^2+(\omega^2+\omega_t^2)^2+2\omega^2(2\omega_t-\omega_c)^2}{2\alpha_t^{-2}\{[\omega^2-\omega_t(\omega_t-\omega_c)]^2+\omega^2\alpha_t^2(2\omega_t-\omega_c)^2\}^2} \quad (9)$$

for the parallel configuration and

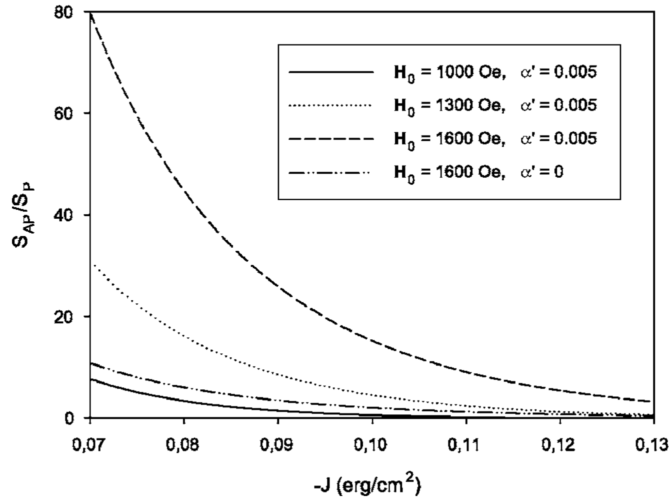

FIG. 2. The ratio $S_{\mathrm{AP}}/S_{\mathrm{P}}$ of the noise powers as a function of the coupling strength $-J$, for some values of the applied external field in the parallel configuration (in the antiparallel configuration, the external field is zero). The damping has been set to $\alpha_0=0.01$ and the anisotropy field to $\omega_c/\gamma=10$ Oe, with the experiments by Covington *et al.* (Ref. 8) in mind.

$$X_{\mathrm{AP}} = \left(\frac{\omega^2\alpha_t+\omega_c^2\alpha_0}{[\omega^2+\omega_c(2\omega_x-\omega_c)]^2+4\omega^2(\omega_x\alpha_0-\omega_c\alpha)^2}\right)^2 \quad (10)$$

for the antiparallel configuration. Here, we set the external field to zero for the antiparallel configuration and assume small damping, $\alpha\ll 1$. The integration over frequency in Eq. (8) reflects the quadratic dependence of the resistance noise on the magnetization noise in the time domain [see Eq. (3)]. $\omega_t=\omega_0+2\omega_x$ and $\alpha_t=\alpha_0+2\alpha'$ (note the difference with $\alpha=\alpha_0+\alpha'$) are the frequency and damping of the antisymmetric mode $\delta\mathbf{m}^-(t)$ in the P configuration.[15] The differential $\partial R/\partial\cos\theta$, as calculated by magnetoelectronic circuit theory,[17] depends only weakly on the magnetic configuration[21] and is taken in the following to be a constant. The ratio $S_{\mathrm{AP}}/S_{\mathrm{P}}$ of the noise powers as a function of the static coupling strength $-J$ is shown in Fig. 2 for some values of the applied external field in the parallel configuration. As expected, the noise ratio increases with increasing external field, since this field stabilizes the P configuration. It is also easily understood that the noise ratio decreases with increasing coupling strength, because the coupling stabilizes the AP configuration while destabilizing the P configuration.

Figure 2 emphasizes the importance of including the dynamic exchange coupling. If disregarded, i.e., $\alpha'=0$, the ratio $S_{\mathrm{AP}}/S_{\mathrm{P}}$ is substantially smaller. To understand this surprising result, consider the derivation of the expressions for S_{P} and S_{AP}: The noise S_{P} is caused by the antisymmetric mode $\delta\mathbf{m}^-(t)=\delta\mathbf{m}_1(t)-\delta\mathbf{m}_2(t)$, which, as can be seen from Eq. (9), is strongly damped by $\alpha_t=\alpha_0+2\alpha'$.[15] The noise S_{AP} in the AP configuration, on the other hand, is caused by the mode $\delta\mathbf{m}^+(t)$, which is relatively weakly damped. Since, according to the FDT, a larger damping is associated with stronger stochastic fields, the mode $\delta\mathbf{m}^-(t)$ in P should be agitated stronger than the $\delta\mathbf{m}^{+}(t)$ AP mode. At first sight, our results for the effect of α' on the ratio $S_{\mathrm{AP}}/S_{\mathrm{P}}$ thus seem to violate the FDT. However, as emphasized above, the damping affects not only the stochastic fields but also the magnetic response of the magnetization to these fields. Since the resistance noise depends *quadratically* on the magnetization noise and *quartically* on the linear-response function, a relatively suppressed response of the antisymmetric P mode turns out to be more important than the increased stochastic fields. As a result, S_{P} is significantly reduced as compared to S_{AP} when the dynamic exchange is included.

We conclude from Fig. 2 that, depending on parameters such as the exchange coupling and the applied magnetic field, the noise power can be much higher in the antiparallel than in the parallel configuration, in agreement with the experimental results by Covington *et al.*[8] on multilayer pillars. In these experiments, the magnetizations reached the parallel alignment for external magnetic field of $\gtrsim$1500 Oe. Whereas we treated spin valves with two ferromagnetic films, Covington *et al.* dealt with multilayers of 4–15 magnetic films. However, the difference between the noise properties of bilayers and multilayers should be quite small, since the only local structural difference is the number of neighboring ferromagnets. This assertion is supported by the experiments by Covington *et al.* that did not reveal strong differences for nanopillars with 4–15 layers.

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