Journal of Magnetism and Magnetic Materials 374 (2015) 740–743

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

# Enhanced stability against spin torque noise in current perpendicular to the plane self-biased differential dual spin valves

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ARTICLE INFO

*Article history:*
Received 1 October 2013
Received in revised form
14 August 2014
Available online 16 September 2014

*Keywords:*
Read-head
Spin transfer torque
Noise
Hard-disk drives

ABSTRACT

We present a detailed study of spin-transfer torque induced noise in self-biased differential dual spin valves (DDSV) which could be potentially used as magnetic read-heads for hard-disk drives. Micromagnetics studies of DDSV were performed in all the major magnetic configurations experienced by read-heads and we show that in every case, self-biased DDSV provide a much stronger stability against spin-transfer torque noise than conventional spin valves. Provided are also insights on the influence of the dipolar interlayer coupling, shape anisotropy, exchange bias and relative orientation between the 2 free layers. Our results demonstrate the viability of DDSV read-heads for future hard disk drives generations.



## 1. Introduction

With hard-disk drive industries setting the areal density milestone for magnetic data storage at more than 10 Tb/in.$^2$ in the next decade [1], new challenges arise from the shrinking dimensions of the media bits' size. New read- and write-heads paradigms have to be developed in order to meet the required physical specifications [2]. Thanks to their inherent differential nature, DDSV read-heads are expected to overcome the shield to shield spacing limitation of current magnetic tunnel junction based single spin-valves read-heads [3]. Nevertheless, more studies, both theoretical and experimental, are required to prove their viability. Indeed, apart from fabrication difficulties, one fundamental issue of DDSV, and more generally of all magnetic read-heads, is the drop of the signal to noise ratio as sensor dimensions are reduced. While Johnson- and mag-noise have already been thoroughly studied [4], no reports on spin-torque noise have yet been reported for DDSV. The present paper fills the gap. In contrast to MRAM devices, STT is detrimental to read-heads as it induces magnetic instabilities, therefore noise [5]. It is expected to be the major limiting factor of read-heads [4] towards 10 Tb/in.$^2$.

A typical DDSV is composed of 2 spin valves in series, separated by a non-magnetic conducting gap layer. Each spin valve is made of a free layer, a non-magnetic conducting spacer layer and a reference layer. The magnetizations of the 2 reference layers are oriented anti-parallel one another thanks to the interlayer dipolar coupling. We have used OOMMF [6] to model a simplified $26 \times 32\ \mathrm{nm}^2$ section (aspect ratio AR$\sim$1.2) DDSV consisting in 2 $Co_{90}Fe_{10}$ free layer (3 nm thickness each) separated by a Ru gap layer (2 nm), unless specified. Interlayer exchange coupling $\sigma$ is considered as zero unless mentioned. The free layers magnetizations point along $\pm y$ (track width, TW), which is the easy axis, while the reference layers are pinned along $\pm z$ (stripe height, SH) as depicted in Fig. 1. The use of synthetic antiferromagnetic reference layers ensures that the magnetic flux closes within the synthetic antiferromagnet structure, hence the simplified trilayer model [7]. We do not consider noise stemming from these synthetic antiferromagnets structures as they are similar in both single spin valves and DDSV [8,9]. Since CoFe/Ru interfaces have a weak (negative) interfacial spin asymmetry and high interfacial spin memory loss, we consider the 2 spin valves to be independent from a transport point of view in first approximation [10,11]. Only a quantitative analysis of the magnetoresistance of a DDSV would require a full drift–diffusion description, since Ru can either lead to an increase or decrease of the magnetoresistance [12]. Additionally, the antisymmetry of the reference layers magnetizations allows us to use a single spin polarization constant, because for a given current, the spin torque has the same direction in both free layers, only different amplitudes. We thus model the spin-torque effect after Slonczewski [13]

$$\frac{\partial m}{\partial t} = -|\gamma|\vec{m} \times \vec{H}_{eff} + \frac{\alpha}{M_s}\left(\vec{m} \times \frac{\partial \vec{m}}{\partial t}\right) + \frac{J}{e} p_i g \mu_B (\vec{m} \times (\vec{m}_s \times \vec{m}))$$

where $J$ is the charge current density, $\vec{m}_s$ the unit spin polarization vector, $p_i = J_s/J$ the ratio of spin polarized over charge current entering the free layer, $\vec{m}$ the magnetization vector, $\gamma$ the

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http://dx.doi.org/10.1016/j.jmmm.2014.08.102
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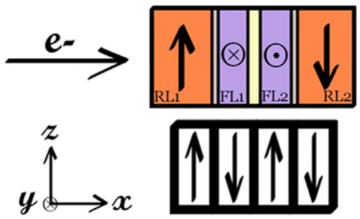


**Fig. 1.** Geometry of the simulated DDSV. The arrows represent the magnetization direction. Also indicated are the electrons direction for positive current and a typical media.

gyromagnetic factor, $\alpha$ is the damping constant and $g$ is the Lande factor of each free layer. In our definition, a positive current is defined as the direction of electrons flow from the SV1 to SV2.

A modification to the OOMMF code was made in order to account for the difference in amplitude at the 2nd spin valve due to electron backscattering [14]. While the dynamics of the spin accumulation have to be evaluated in specific cases such as wavy structures [15,16], most of the physics of our device regarding STT noise can be captured by considering 2 spin valves independent from the transport point of view but coupled by dipolar interaction and exchange bias. Given the small section of the sensor, the Oersted field was neglected throughout this study.

In order to determine STT-induced noise, we let the system relax between $t=0$ and $t_0$ before saving the magnetization data until $t_1$ and then calculate the sensor output $s(t)$ using a phenomenological current perpendicular to the plane giant magnetoresistance (CPP-GMR) model:

$$s(t) = \frac{\Delta RA}{RA} \times RA \times J \times [\cos\,\theta_1(t) + \cos\,\theta_2(t)]$$

where $RA$ and $\Delta RA/RA$ are assumed to be 50 m$\Omega$ $\mu$m$^2$ and 10% respectively for CPP-GMR based DDSV, $J$ is the current density and $\theta_1(t)$ and $\theta_2(t)$ are the angles between each free layer and their respective reference layer magnetization. The power spectral density (PSD) is calculated accordingly:

$$\mathrm{PSD}(f) = \lim_{t_0 \to t_1} \frac{1}{t} E\left[|s(f)|^2\right]$$

where $E$ is the expectation value and $s(f)$ the FFT of $s(t)$. We choose $t_0=25$ ns which is a high value (it corresponds to a data rate upper cut-off frequency of 40 MHz) but accommodates the artificial increase of the initial simulation-related relaxation time. $t_1=50$ ns yields reasonably clean FFT spectra while keeping the computation time low enough. The root mean square value of the noise $N$ is then given by integrating the power spectral density over the available frequency range and taking its root value:

$$N = \sqrt{\sum_{f>0} 2\mathrm{PSD}(f)\Delta f}$$

where $\Delta f$ is the frequency resolution of the FFT.

Shown in Fig. 2(a) is a plot of the simulated absolute noise of a DDSV for a 50 mT uniform (black squares) and differential (-,+ and +,- configurations are represented by open circles and open triangles, respectively) magnetic fields. We did not consider the case of a uniform $-50$ mT field, as it would give the same results with opposite current sign. As expected for a uniform field, STT is only observed for one current direction [17]. This corresponds to the worst case regarding STT noise for a DDSV, because the torque tends to destabilize both free layers' magnetizations, whereas for differential fields, STT only destabilizes one free layer at a time, yielding lower noise levels. The notable difference in noise levels between the 2 differential fields configurations is due to the asymmetry of effective spin polarization $P_i(J>0) \neq P_i(J<0)$ for each spin valve [14]. For $(+,-)$ configuration, The FLs in both

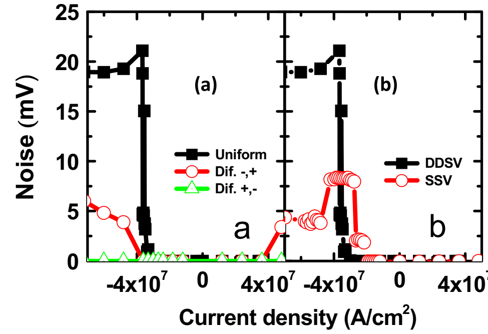


**Fig. 2.** STT induced noise as a function of the applied current (a) for atypical DDSV in uniform and differential fields and (b) with a uniform field for a typical single spin valve and a DDSV. The magnetic field amplitude is 50 mT along the SH direction.

the SVs align parallel to their respective RLs. When the electrons flow from SV1 to SV2, FL1 feels the forward torque in parallel state which results in no noise at the SV1. However, FL2 feels the torque towards anti-parallel state due to reflected electrons which results in noise at SV2. For $(-,+)$ configuration, the FLs in both the SVs align anti-parallel to their respective RLs. When the electrons flow from SV1 to SV2, FL1 feels forward torque in parallel state results in noise at SV1 and FL2 feels reverse torque in anti-parallel state which results in no noise at SV2. The STT noise is higher in $(-,+)$ configuration compared to $(+,-)$ as the noise due to forward torque is always higher compared to the reverse torque. The argument is valid for DDSV irrespective of the current direction as the two SVs are mirroring each other.

A comparison between similar single spin valve (SSV) and DDSV is made in Fig. 2(b) for a uniform 50 mT field. In a self-biased DDSV, the two FLs experience an additional dipolar field coupling which aligns their magnetizations anti-parallel one another. The average dipolar field is found to be ~70 mT, at a GL thickness of 2 nm. To make a reasonable comparison between SSV and DDSV, an additional hard bias field of 70 mT is therefore applied along the easy axis (TW) direction to the SSV. We find a critical current density for the onset of STT noise in SSV of $2.6 \times 10^7$ A/cm$^2$ which is lower than the critical current density ($4 \times 10^7$ A/cm$^2$) of the DDSV, which implies that DDSV are more stable against STT noise compared to the SSV. The higher critical current density in case of DDSV can be attributed to differences in bias field distributions between the 2 types of sensors. Self-biased DDSV indeed possess a more inhomogeneous field along the TW direction with higher values at the edges which help stabilize them. We have also calculated thermal noise adding an irregular fluctuating time-dependent magnetic field (OOMMF package Thetaevolve – time step set to $10^{-16}$ s) and found that whenever $|J| > |J_c|$, the STT-induced noise level is so high that mag-noise becomes negligible. Thermal stability imposes the ground floor noise below the onset of STT and can be tuned by adjusting the shape anisotropy of the sensor.

To further ascertain the influence of the interlayer dipolar coupling, we have modelled additional DDSV with varying gap layer thicknesses ranging between 2 nm and 10 nm. Increasing the thickness of the gap layer should indeed lead to a decrease of the dipolar coupling strength, other parameters of the simulation being constant. Results presented in Fig. 3 and unambiguously demonstrate the importance of $H_d$ as $J_c$ decreases with gap layer thickness, as expected from dipole-dipole interaction between 2 thin magnetic films. A strong interlayer dipolar coupling is thus highly desirable to prevent STT noise.

Ru being a transition metal across which a strong exchange bias is observed thanks to the RKKY mechanism [18], we have also assessed its influence on the dynamics of the free layers

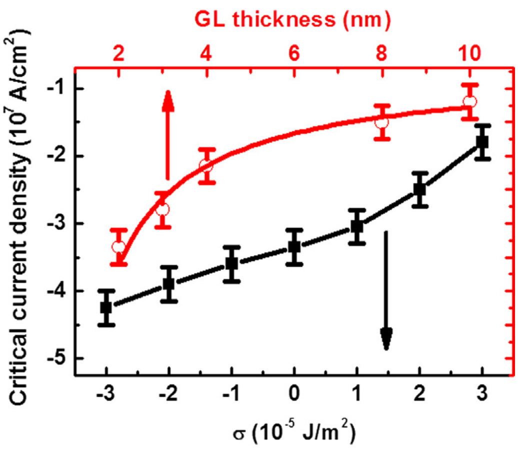


**Fig. 3.** Critical current density as a function of the exchange bias constant $\sigma$ in black squares (the line is only a guide for the eyes) and as a function of the gap layer thickness in red open circles. The fitting is guide for the eyes. Error bars express the uncertainty due to reading errors.

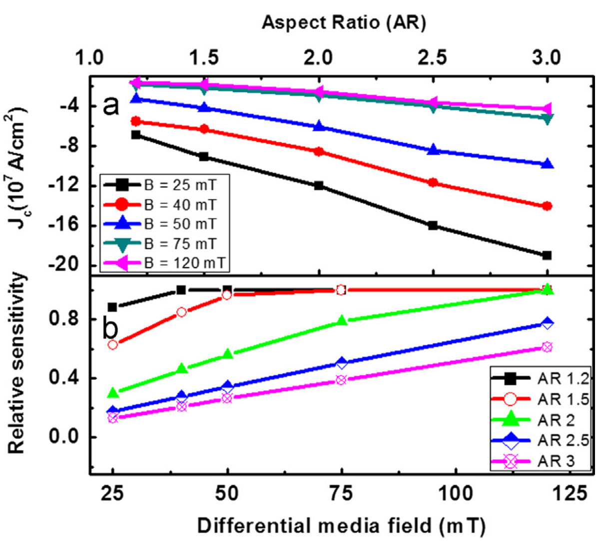


**Fig. 4.** (a) Critical current density as a function of the aspect ratio (AR) at various media fields. (b) The corresponding relative sensitivity as a function of differential media field.

magnetizations. The exchange constant lies around $|\sigma| = 10^{-5}$ J/m$^2$ for a 2 nm thick Ru layer [19,20] and the simulations are carried out for both positive and negative values to take into account the oscillating behaviour of the coupling as a function of Ru thickness. The results, also shown in Fig. 3 are straightforward: $\sigma > 0$ ($\sigma < 0$) results in a decrease (increase) of $J_c$ as a positive (negative) value of $\sigma$ stabilizes a parallel (antiparallel) alignment of magnetizations. $\sigma < 0$ reduces the sensitivity to STT-noise because it adds an effective field which stabilizes the antiparallel alignment of both free layers, concurrently with the dipolar field. Anti-ferromagnetic coupling is highly desirable when designing a self-biased DDSV sensor.

To get an insight into the effect of shape anisotropy on the critical current density, we have varied the aspect ratio (TW/SH) of the FL from 1.2 to 3. The critical current density ($J_c$) is calculated at different homogenous media fields ranging from 25 mT to 120 mT as shown in Fig. 4(a). As expected, the critical current density ($J_c$) is found to increase with aspect ratio since a higher anisotropy field along the TW direction stabilizes the two FLs against STT noise. However, the relative sensitivity of the reader also drops dramatically as shown in Fig. 4(b). The relative sensitivity is taken as the

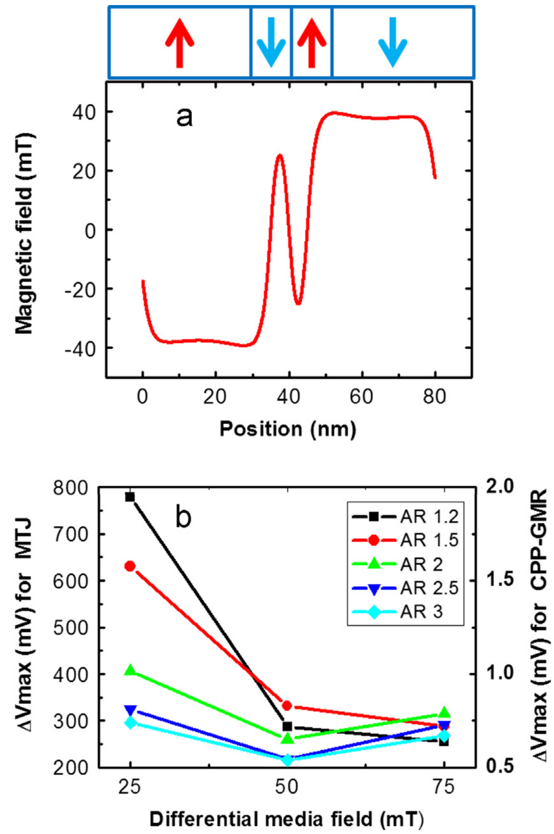


**Fig. 5.** (a) Typical distribution of transverse magnetic fields experience by the FL at a media-head distance of 2 nm. (b) The maximum signal output of the DDSV reader as a function of differential media field at different dimensions of the FL. The voltage has been calculated for both the MTJ and CPP-GMR based DDSV.

cosine of the relative angle between the FL1 and RL1. For a comparison between $AR = 1.2$ and 3 at a media field of 50 mT, the critical current density rises $\sim 3$ times, but the sensitivity of the DDSV reader drops 4 times. We therefore need to consider these two aspects while tuning the dimensions of the reader.

In order to study the effect of the relative orientation of the FLs on the critical current density, we have varied the uniform media field from 25 mT to 120 mT. The critical current density is found to drop with increasing media field, which indicates that STT noise is low when the FLs are aligned in the quiescent state. In a self-biased DDSV, the two FLs always form a flux-closure in the ground state (no external field and no current). The uniform media field acts against the dipolar coupling to break the anti-parallel alignment between the FLs, therefore rendering the device more sensitive to STT-noise. From Fig. 4(a), it is worth noting that the drop in critical current density is not so significant when the media field changes from 75 mT to 120 mT. This is due to fact that the both FLs are almost saturated at 75 mT along SH direction above which the effect of the media field on the critical current density becomes negligible.

The maximum signal output of DDSV readers below the threshold of STT-noise for various dimensions is calculated for both MTJ and CPP-GMR based DDSV read-heads according to the following formula:

$$\Delta V = \frac{\Delta RA}{RA} \times RA \times J_{max} \times v$$

where $v$ is the sensitivity of the read-head, $J_{max}$ is the current density applied to the reader is considered as 80% of the critical current density ($J_{max} = 0.8 J_c$), $RA$ and $\Delta RA/RA$ are assumed to be 50 m$\Omega$ $\mu$m$^2$ and 10% for CPP-GMR based DDSV and 1 $\Omega$ $\mu$m$^2$ and

100% for MTJ based DDSV, respectively. Here $A$ is the cross sectional area of the FL and $R$ is the resistance across the DDSV. A typical magnetic field distribution above a 10 nm-bit length media at a media-head distance of 2 nm is shown in Fig. 5(a) and points out that the overlap of magnetic fields generated by each nearby bit leads to variable media field values, depending on the magnetic bits sequence. When two bits of opposite magnetization are next to each other, the field variation shows that the differential field experienced by the read head is lower whereas the field relatively increases when two bits of same magnetizations are next to each other. In order to obtain realistic output values, $J_{max}$ is then calculated for the worst case of STT (corresponding to uniform fields) while $\nu$ is determined at the corresponding differential field. For differential fields of resp. 25 mT, 50 mT and 75 mT, we find uniform fields of resp. 39 mT, 78 mT and 118 mT. The maximum output voltage is then plotted against the media differential field in Fig. 5(b). The maximum allowed output voltage is found be the highest at low aspect ratio and low media differential field, because the gain in sensitivity is offset by the drop in critical current density when these parameters are increased.

In summary, micromagnetic simulations of self-biased DDSV and single spin valve sensors have been performed taking into account Slonczewski's spin transfer torque model. We have found that DDSV sensors possess an intrinsic increased stability against STT-induced noise compared to single spin valves which is mainly due to dipole–dipole coupling between the 2 free layers' magnetizations. We have shown that the exchange bias should be set with a negative $\sigma$ in order to also favour an anti-parallel alignment. These findings set one design rule that the gap layer thickness must be minimized in order to maximize the dipolar interlayer coupling and the exchange bias, but it must be carefully controlled to avoid a positive RKKY coupling. Shape anisotropy was also found to increase the stability against STT, due to an increase in anisotropy field (but this also applies to a single spin valve) at the cost of a reduced sensitivity to the differential media field. Higher the uniform media field, DDSV are less stable against STT and maximum signal output is obtained at lower aspect ratio and lower media field. The results presented here are useful for the optimization of DDSVs for ultrahigh density hard disk recording.

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