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Noise study of magnetic field sensors based on magnetic tunnel junctions

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Abstract. Low frequency noise has been studied for two types of magnetic field sensors based on magnetic tunnel junctions (MTJ). The first structure, composed of a few large MTJs, is designed for low noise applications; the second one, composed of hundreds of small MTJs, is designed for general purposes. At low frequency, both structures exhibit $1/f$ noise, but with very different amplitudes. The sensors for general purposes show a much higher noise level compared to the low-noise sensors. However, the sensitivity of the low noise sensors is much smaller compared to the other ones. Thus, the limit of detection, defined as the ratio of noise and sensitivity, turns out to be roughly the same for both technologies. Using the advantages of each sensor could help to design a sensor with an improved limit of detection.

1. Introduction

Magnetic field sensors based on Magnetic Tunnel Junctions (MTJs) could become a serious alternative to other technologies like Hall effect devices [1], thanks to their low power consumption, good sensitivity and robustness against radiations. These junctions are composed of two ferromagnetic layers separated by a tunnel barrier and their resistance depends on the relative orientation of the magnetizations of both layers [2]. To use them at low-frequency, such magnetic field sensors need to have low noise levels. Moreover, at low frequency, $1/f$ noise may restrict the limit of detection of the sensors [3]. This noise can be expressed as $\frac{\alpha_{Hooqe} V^2}{Af}$, where V is the voltage across the MTJ, A its area, f the frequency and α_{Hooqe} the Hooqe coefficient. This noise is usually high compared to *Johnson* or *shot noise* and has to be reduced in order to improve the performances of MTJ-based sensors at low frequencies. Its proportionality factor α_{Hooqe} called Hooqe coefficient [4] characterizes the noise level. It can be understood as the *noise quality factor* of the junction and is a good parameter to compare different technologies or solutions [5]. Another important characteristics of a magnetic sensor is its limit of detection, *i.e.* the lowest measurable field under operating conditions. It is defined as the ratio between noise and sensitivity and is expressed in $T/\sqrt{\text{Hz}}$. It is frequency-dependent due to $1/f$ noise [6]. Its value is therefore estimated at a given frequency.



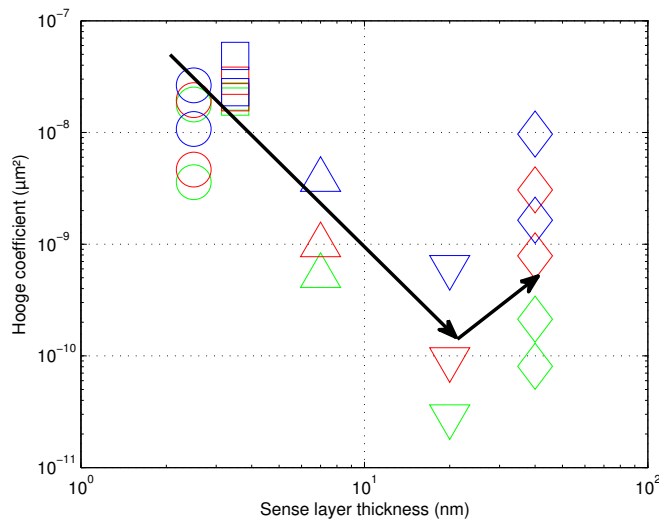


Figure 1. Hooge coefficients in parallel state (green), anti-parallel state (red), near operating point (blue) as a function of sense layer thickness. The following stacks (thicknesses in nm): \square (CoFeB/NiFe)3.5; \triangle (CoFeB/NiFe)7; \circ CoFeB2.5; ∇ CoFeB20; \diamond CoFeB40. The black line draws the global observed trend. The Hooge coefficient decreases as a function of sense layer thickness up to a point where the thickness becomes too high and where we suspect magnetic properties are deteriorating.

2. Samples and experiments

Two types of sensors were studied. The first type (Sensors A) consists of rectangular junctions with a surface from $4 \mu\text{m}^2$ to $20 \mu\text{m}^2$, specifically designed for low-noise purposes [7]. In these sensors, there are no more than 3 junctions in series. The second type of sensors (Sensors B) consists of arrays of small circular junctions with a surface of $\approx 0.05 \mu\text{m}^2$. These arrays are composed of respectively, 104, 480 and 600 MTJs, in a serial / parallel configuration with respectively N_s and N_p junctions. In both cases, the sense layer is either a single CoFeB layer or a CoFeB/NiFe bilayer. Noise has been measured using a SR780 Stanford Research Spectrum Analyzer that can perform noise measurements up to 100 kHz. The noise signal is filtered and amplified using a Stanford Research SR560 low-noise pre-amplifier. The devices are biased with a battery and a potentiometer [8]. Custom coils and electromagnets are used to apply a magnetic field on the sample. Noise measurements are corrected from the measurements performed at zero bias voltage (background noise). Note that the *Johnson noise* is included in the background noise.

3. Noise in sensor A

Noise was studied for a wide range of magnetic fields along the easy and hard axes leading to a full noise characterization of these samples. Several samples were studied with different sense layer compositions and thicknesses, and different junction sizes. The results are summarized in figure 1. The lowest noise levels are recorded when the magnetizations of the reference and sense layers are parallel. Noise in anti-parallel state is always higher than in parallel state, which is consistent with previous observations showing that the noise in anti-parallel state is roughly twice the noise in parallel state [5, 9]. Nevertheless, there is no constant factor between both noise levels in our case. All other things being equal, the Hooge coefficient is expected to decrease inversely to the sense layer thickness [10]. One can see in figure 1 that the Hooge coefficient is decreasing with the sense layer thickness (see black line) until a certain point where it seems to increase again. The reversal point, which is the best sensor in terms of noise, corresponds to a sensor with a sense layer thickness of 20 nm (CoFeB20). After this limit, increasing the thickness seems to deteriorate the noise level. However, the aspect ratio varies with the junction size which has an important impact on magnetic properties and thus on noise [11, 12]. Further studies are necessary to distinguish the impacts of the junction size, aspect ratio and magnetic

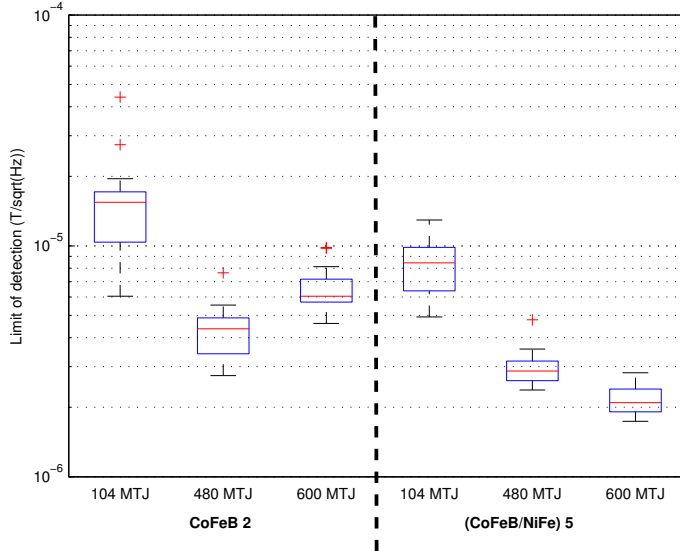


Figure 2. Limit of detection (at 1 Hz) as a function of number of MTJs in sensors B for two sense layers. Each box comprises 18 samples. Increasing the sense layer thickness and/or increasing the number of MTJs improves the limit of detection. Note that for 480-MTJ-CoFeB2 sensors, the median of limits of detection ($4.4 \times 10^{-6} T/\sqrt{Hz}$) is better than expected ($7 - 8 \times 10^{-6} T/\sqrt{Hz}$)

volume. However, minimizing noise is not sufficient for obtaining a high performance sensor. The sensitivity must also be high. To optimize the properties of a sensor requires to find the best compromise between noise and sensitivity, which means to lower the limit of detection.

4. Noise in MTJs arrays – Sensors B

We performed a statistical study of noise in sensors composed of arrays of hundreds of MTJs. Three types of sensors with different numbers of MTJs have been considered. Sensors with two different sense layers are compared: 2 nm thick CoFeB layer or 5 nm thick (CoFeB/NiFe) bi-layer. All other things being equal, the Hooge coefficient should decrease as the inverse of the sense layer thickness [10]. In our case, the expected reduction should be 2.5 which is larger than the observed reduction factor of 1.71 ± 0.24 . This can be explained by the fact that the sense layer material was also changed: we compare a pure CoFeB sense layer and a bi-layer of CoFeB and NiFe. Taking into account the magnetizations of CoFeB and NiFe (respectively 1250 emu/cm^3 and 800 emu/cm^3), we can estimate a thickness of 3.92 nm for an equivalent layer composed only of CoFeB. This value would lead to a noise decrease by a factor 1.96, close to the factor observed experimentally. We can further analyze these results and consider the limit of detection of these sensors as a function of the sense layer composition and number of junctions. For each sensor we measured its sensitivity and its highest noise level inside the sensitive region, leading to an over-estimation of the sensor limit of detection. Figure 2 shows a clear dependence of the limit of detection as a function of the number of junctions and as a function of the sense layer thickness. We have calculated that the limit of detection should decrease as the square root of the number of junctions $\sqrt{N_s N_p}$. By comparison to the 104-MTJ sensors, the limit of detection of 480-MTJ and 600-MTJ sensors should decrease respectively by a factor 2.15 and 2.4. Experimentally observed reduction factor are 3.55 and 2.56 for sensors with CoFeB2, and 2.94 and 4.04 for sensors with (CoFeB/NiFe)5. These reduction factors are higher than expected. However, this discrepancy can be partially explained by the error bars on these data. Let us now compare arrays with an identical number of junctions and different sense layers. The reduction factors of the limit of detection for 104-MTJ, 480-MTJ and 600-MTJ sensors are respectively 1.83, 1.52 and 2.89, to be compared to $\sqrt{1.96} = 1.4$ as calculated above.

These two successive comparisons between experimental results and theoretical expectations show that 480-MTJ-CoFeB2 and 600-MTJ-(CoFeB/NiFe)5 sensors have better performances than expected, probably linked to fabrication details or particular micromagnetic states.

5. Conclusion

In this article we studied two different sensor technologies. The first one is based on micron-sized junctions specifically designed for low-noise applications. This goal is only partially achieved. Although, the Hooge coefficient measured both in saturated states and in sensitive region (10^{-10} to $10^{-9} \mu\text{m}^2$ for the best sensors) is very low, the sensitivity of these sensors is rather low leading to a relatively high limit of detection (around $2 \mu\text{T}/\sqrt{\text{Hz}}$ at 1 Hz for the best sensor A). The second technology studied was based on arrays of small MTJs with a high sensitivity comprised between 50 and $150 V/V/T$. They exhibit higher noise with a Hooge coefficient of the order of $10^{-6} \mu\text{m}^2$. Nevertheless, thanks to their sensitivity, their limit of detection is quite similar to sensor A (down to $1 \mu\text{T}/\sqrt{\text{Hz}}$ at 1 Hz for 600-MTJ-(CoFeB/NiFe)5). Future work will combine the advantages of both types of sensors (A+B). For example, sensors A can be designed with junctions having a smaller aspect ratio or another shape in order to increase the sensitivity, while for sensors B, we can increase the junction size while keeping a large number of junctions, thus reducing the noise level. Further improvements of magnetic materials and anisotropy could also be implemented for both technologies.

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