Noise in MgO barrier magnetic tunnel junctions with CoFeB electrodes: Influence of annealing temperature

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Low frequency noise has been measured in magnetic tunnel junctions with MgO barriers and magnetoresistance values up to 235%. The authors investigated the noise for different degrees of crystallization and CoFeB/MgO interface quality depending on the annealing temperature. The authors report an extremely low $1/f$ noise, compared to magnetic junctions with Al_2O_3 barriers. The origin of the low frequency noise is discussed and it is attributed to localized charge traps with the MgO barriers. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2749433]

The resistance of a magnetic tunnel junction (MTJ) depends on the relative magnetization of the ferromagnetic layers: it is usually low in the parallel configuration (PC) and high in the antiparallel configuration (APC). This effect is used for storage in magnetic random access memory and is now being adopted for read heads in place of giant magnetoresistance (GMR) sensors. The prediction[1,2] and recent observation[3] of tunnel magnetoresistance (TMR) ratios $[(R_{AP}-R_P)/R_{AP}]$ as high as 1000% in MTJs with MgO barrier make those devices very attractive candidates to outclass GMR in high-resolution sensors. However, a high TMR ratio is not enough to make a good magnetoresistive sensor, since its performance is determined by the sensitivity which is the output voltage per unit field divided by the voltage noise.

The noise level is as important as the magnitude of the signal itself. From earlier studies on MTJs with Al_2O_3 barriers, the noise can be traced back to three sources. The first is the frequency-independent thermal noise, which is an intrinsic property of a tunnel junction that defines the ultimate noise limit. Here, we will focus on the two other contributions to the noise, which may be reduced or even eliminated provided the appropriate parameters are known. At low frequencies, noise is dominated by a $1/f$ component, which is analogous to $1/f$ noise in conductors. It is quantified by the Hooge-like parameter $\alpha=AfS_V(f)/V^2$, expressed in units of area; A is the surface area of the junction, $S_V(f)$ the noise power spectrum, and V the voltage drop across the tunnel barrier. Its origin is not fully understood, and, in particular, the influence of magnetization is still unclear although it is commonly observed that α is higher in the APC than in the PC.[4,5] The quality of the metal-barrier interface may also play a role in the $1/f$ noise.[4] The third component in MTJs is random telegraphic noise (RTN), namely, discrete fluctuators in the voltage-time traces associated with a Lorentzian-like spectrum. It is characterized by a strong sample-to-sample random of its amplitude and switching rate and it is interpreted either in terms of charge trapping or magnetic domain fluctuations.[6]

In this letter, we discuss low frequency noise properties of MTJs with a MgO barrier which exhibit TMR ratios up to 235%. Our focus is on the annealing temperature, which is the crucial parameter for a high TMR ratio. We discuss the origins of the noise, based on calculated transport properties;[1,2] those calculations have been rendered possible by the crystalline structure of MgO and could not have been performed for amorphous Al_2O_3 barriers.

Our MTJs consist of Ta 5/Ru 50/Ta 5/NiFe 5/IrMn 10/CoFe 2/Ru 0.7/CoFeB 3/MgO 2.5/CoFeB 5/NiFe 5/Ta 5 multilayer stacks grown by magnetron sputtering (the order from the bottom electrode to the top with thickness being given in nanometers). Further details on the growth process can be found in Ref. 7. The multilayer stacks are patterned into 16×16 and 24×24 μm^2 junctions by UV lithography (series A and B, respectively), then annealed in 0.8 T for 90 min at 250 °C (B2), 300 °C (B3), and 375 °C (A and B4). MTJ B1 is not annealed. Annealing aims at improving the degree of crystallization of the ferromagnetic layer that is amorphous as deposited: the Δ_1 band responsible for a good band matching is created by annealing, thus yielding high TMR ratios.[2] If the temperature is further increased, the MR drops because of diffusion of Ru and Mn atoms from the artificial antiferromagnetic layer ruining the exchange bias. Furthermore, annealing also improves the quality of the CoFeB/MgO interface as it has been suggested experimentally in Ref. 7. Noise measurements were performed in a cryostat at 300, 77, and 4 K. We used a INA103 preamplifier in an electronic circuit optimally designed for our MTJs resistances (ranging from 1 to 20 kΩ), yielding a background noise of 3 nV/$\sqrt{\text{Hz}}$. The amplified signals are digitalized at 50 kHz by a 16 data bit acquisition card and numerically processed. All noise data are measured at zero magnetic field, the magnetic configuration having been set by applying a saturating field and switching it off.

Let us consider first the noise signature of the junction A, which was annealed at $T_a=375$ °C and presents a TMR ratio of 235%. Its ferromagnetic layers are well crystallized, and the CoFeB/MgO interface is sharp. In Fig. 1, we show the power spectral densities $S_V(f)$ for several bias currents at 77 K. High frequency noise is dominated by a frequency-independent component that corresponds to the thermal noise, indicated by the dashed lines in the graph. At low frequency, $1/f$ noise is observed. We measured room temperature values of α of the order of 10^{-10} μm^2. As the

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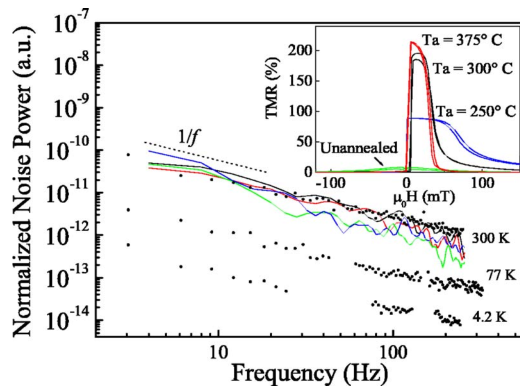

FIG. 1. (Color online) Power spectral densities $[S_V(f)]$ of a 375 °C annealed MTJ measured at 77 K in the PC, for $I=0$, 20, and 50 μA, corresponding to $V=0$, 106, and 306 mV. The dashed lines represent the extrapolation to low frequencies of the white noise that increases with the current. Inset: Bias dependence of the TMR ratio normalized by the zero bias TMR ratio (open circles) and voltage noise at 12 Hz expressed in nV/Hz^2 in the PC (squares) and APC (triangles) plotted against the voltage. The slope of the solid lines is proportional to $\sqrt{\alpha}$. The dotted line represents the amplifier background noise.

TABLE I. $1/f$ noise level represented by α (expressed in μm^2) at different temperatures, for both magnetic configurations and voltage signs. Values are given within 10% error bars accounting for the statistical dispersion.

	α parallel		α antiparallel	
T (K)	$V>10$	$V<0$	$V>0$	$V<0$
300	2.5×10^{-10}		5.0×10^{-10}	
77	3.2×10^{-11}	2.0×10^{-11}	1.3×10^{-10}	6.5×10^{-11}
4.2	9.6×10^{-13}	2.7×10^{-13}	2.8×10^{-12}	3.0×10^{-12}

junction is cooled down to 4.2 K, α decreases by two orders of magnitudes (Fig. 2). It is remarkable that in our MTJs with a MgO barrier, α is at least two orders of magnitude lower than in Al_2O_3 MTJs at a given temperature.[4,6,8,9] It must also be noted that the V^2 dependence of the $1/f$ noise power S_V is linear (inset of Fig. 1 displays square-root values). This means that α is practically constant in the explored range of voltages ($V\approx0-400$ mV), while the TMR ratio drops by 50%. Also noteworthy is the asymmetry of α depending on the sign of the voltage. The $1/f$ noise is significantly higher for positive voltages, when the electrons pass from the bottom up to the top electrode, than for negative voltages (Table I). We will discuss these points later.

Now, we focus on the effect of the annealing temperature on the magnetoresistance which is shown in the TMR versus magnetic field curves (inset of Fig. 2). The unannealed junction (B1) exhibits a very low TMR ratio, and in the annealed junctions with T_a up to 375 °C the TMR ratio increases (B2–B4, respectively, MTJ A having similar behavior to B4). We measured the voltage noise at $T=300$ K for different annealing temperatures. The normalized noise power spectra $S_V(f)A/V^2=\alpha/f$ for MTJs B1-4 are presented in Fig. 2 (solid lines). Interestingly, all spectra lie within the statistical deviation, meaning that the magnitude of the $1/f$ noise does not vary significantly with T_a. Hence, it can be directly associated neither with the degree of crystallization of the ferromagnetic electrodes, nor with the quality of the CoFeB/MgO interface. Likewise, no correlation can be found between the $1/f$ noise and the TMR ratio.

We also observe occurrences of RTN in the MTJ annealed at 250 °C (B2) in addition to the $1/f$ noise. The switching rate of the associated fluctuator is extremely sensitive to the current and to the applied magnetic field and it is not reproducible, as in Al_2O_3 based MTJs.[6] It is also strongly dependent on the temperature: Fig. 3 illustrates the variation of the RTN as the sample is cooled down. Annealing at 250 °C is not high enough to completely crystallize the ferromagnetic layers as can be seen from the moderate TMR ratio (inset of Fig. 2); some crystallographic defects remain, which is favorable for the creation of magnetic domains. In contrast, we did not measure any RTN in the MTJ annealed at 375 °C, in which the CoFeB layers are fully, or at least better crystallized. We attribute the RTN to fluctuating magnetic domains in the ferromagnetic electrodes, as was already been proposed in AlO based MTJs.[6]

Although layer magnetization fluctuations seem to be responsible for the RTN, we doubt that they are an ingredient of major importance in the $1/f$ noise here, despite the dependence of α on the magnetic alignment of the layers. Indeed, resistance fluctuations originating from magnetization fluctuations should strengthen as the TMR ratio increases with T_a, which is contradicted by our results. Similarly, the dependence of α upon the magnetic alignment (see Table I) should be related to the TMR ratio, whereas α increases in the same proportion (a factor of 2–3) in Al_2O_3 MTJs with only 40% TMR.[4,6] Instead, we attribute the $1/f$ noise to charge trap-

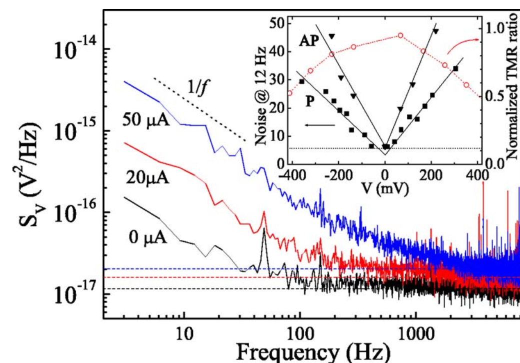

FIG. 2. (Color online) Normalized noise power spectra $S_V(f)A/V^2=\alpha/f$. MTJ A (dots) at 300, 77, and 4.2 K, for $V=130$, 306, and 901 mV, respectively. Solid lines are spectra measured at $V=500$ mV in three junctions annealed at $T_a=250$, 300, 375 °C (B2–B4) and one unannealed junction (B1). All data are measured in the PC. Inset: TMR ratio vs magnetic field of junctions B1–B4.

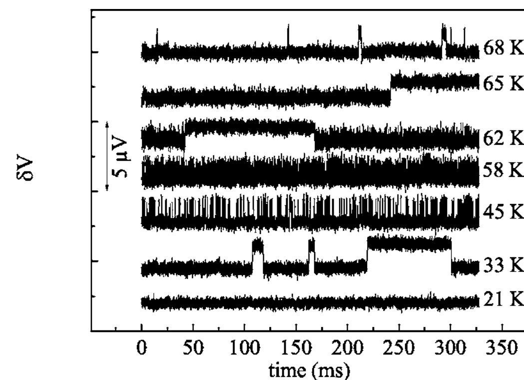

FIG. 3. Voltage fluctuations at different temperatures in the 250 °C annealed sample. The bias current is kept constant at $I=0.2$ mA which corresponds to an output voltage of a few volts, in this range of temperatures.

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ping in the insulating barrier, as is the case in nonmagnetic tunnel junctions.[10] The way the electrons tunnel through the barrier depending on the layer magnetization can be considered. The conductivity channels have been detailed in calculations by Butler *et al.*[2] It has been shown that conductivity in the PC is dominated by s electrons of the Δ_1 band which have small parallel components of their wave vector ($k_{\parallel}$). Minority and antiparallel conductivity are due to localized electrons with a given $k_{\parallel}$ whose density of states decays much faster in the MgO barrier than the s electrons. The constancy of α regardless of the existence of the Δ_1 band (determined by T_a) shows that the contribution of this conductivity channel to the noise is negligible and, consequently, that most of the noise comes from electrons with larger $k_{\parallel}$ from either majority or minority band. This is coherent with the fluctuations originating from localized charge traps in the insulator (e.g., magnetic impurities) since they are expected to have more effect on localized electrons than on delocalized ones. Since no s electrons can tunnel in the APC, the noise is higher relative to the resistance than in the PC where a part of the conduction is practically noise-free. Such a noise mechanism is very sensitive to the polarization as can be seen from the asymetry of α with the sign of the voltage (Table I). Depending on whether tunneling electrons come from the thin ($V>0$) or the thick CoFeB electrode ($V<0$), the spin up and spin down populations slightly vary, and so do the conductivity channels, thus leading to different amounts of noise.

In conclusion, the order of magnitude of the Hooge-like parameter α, which is as small as 10^{-12} μm^2 at low temperature in our junctions, regardless of the TMR ratio is very promising for low frequency applications. Neither the TMR ratio, nor the CoFeB/MgO interface quality nor the CoFeB crystallization and magnetic stability is a relevant parameter for the $1/f$ noise in our junctions, which we attribute to charge trapping in the insulating barrier. The random telegraph noise in underannealed junctions is associated with magnetic fluctuations.

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