Low frequency noise due to magnetic inhomogeneities in submicron FeCoB/MgO/FeCoB magnetic tunnel junctions

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We report on room temperature low frequency noise due to magnetic inhomogeneities/domain walls (MI/DWs) in elliptic submicron FeCoB/MgO/FeCoB magnetic tunnel junctions with an area between 0.0245 and 0.0675μm^2. In the small and medium area junctions, we found an unexpected random telegraph noise (RTN1), deeply in the parallel state, possibly due to stray field induced MI/DWs inside the hard layer. The second noise source (RTN2) is observed in the antiparallel state for the largest junctions. Strong asymmetry of RTN2 with current and insignificance of self-field indicate spin torque acting on the MI/DWs in the soft layer by the tunnel current at densities below $5*10^5$ A/cm^2.

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The discovery of tunneling magnetoresistance (TMR) exceeding 100% at room temperature [1-6] has boosted scientific and technological interest in magnetic tunnel junctions (MTJs). In contrast to metallic spin valve structures, MTJs with insulating MgO tunnel barriers show reduced power consumption, high TMR and enhanced out-of plane spin torque [7], converting them into the basic building elements for spintronic devices. While MTJs with sizes of tens of microns (multidomain reversal) are optimal for applications as ultra low noise magnetic field detectors [8], junctions with lateral size below about 100nm and a uniform magnetization reversal are used for, e.g., spin torque magnetic random access memories (ST-RAM) [9], microwave oscillators [10]. Electron transport and especially *low frequency magnetic noise* in submicron MTJs with lateral size of some hundreds of nanometers, i.e. in the range where single magnetic inhomogeneities (MI) [11] and domain walls (DW) play an important role in magnetization reversal, remain poorly understood.

Previous low frequency noise studies of 1/f (magnetic, nonmagnetic and electronic contributions) and random telegraph noise (RTN) focus on MTJs above-micron size with Al_2O_3 [12-14] and MgO [8,15-21] barriers. Recent advances in understanding of magnetic 1/f noise are summarized in Refs. [14,18,19]. Our letter presents both TMR and low frequency noise at room temperature in CoFeB/MgO/CoFeB MTJs with 0.8nm thick MgO barriers and areas ranging from 0.117 μm^2 down to 0.0245μm^2. MTJs of these sizes reveal two qualitatively different, robust and reproducible RTN types related with single MI/DWs. The most unexpected (RTN1) noise source appears at a restricted field range deeply in the parallel state, and is observed only in the medium-smallest size (0.0503 and 0.0245μm^2) MTJs. RTN1 seems to originate from thermally activated fluctuations of stray field induced MI/DW in the magnetically hard ferromagnetic layer. Another robust noise source (RTN2) is found in the largest (0.0565 and 0.0675μm^2) MTJs and is asymmetrically influenced by the tunnel current. The low contribution of self-field suggests an influence of spin torque transfer on the stability of these MI/DWs already at small vertical tunnel current densities.

The layer stack was deposited by magnetron sputtering in a Timaris PVD cluster tool from Singulus Technologies. Its structure is Ta 5/Cu-N 90/Ta 5/Pt-Mn 20/Co-Fe 2.2/Ru 0.8/Co-Fe-B 2/Mg 0.8+1200s oxidation+Mg 0.3/Co-Fe-B 2/Ta 10/Cu-N 30/Ru-7 (thicknesses in nm). The stack was annealed for 90 minutes at 360°C and cooled in a field of 1 Tesla to establish the exchange bias. Using electron beam lithography and ion beam milling the stack was patterned into elliptic tunnel junctions with different sizes: 600nm x 250nm=0.117 μm^2, 430nm x 200nm =0.0675 μm^2, 400nm x 180nm =0.0565 μm^2, 400nm x 160nm = 0.0503μm^2 and 260nm x 120nm = 0.0245 μm^2. The zero bias TMR was between 45% and 160% and R×A (Resistance-Area) products between 3 Ω*μm^2 and 19 Ω*μm^2.

Out of 13 MTJs with TMR at room temperature exceeding 45% (see summary in Fig.1a) we present low frequency noise measurements (1Hz to 10 kHz) for 7 MTJs (closed dots in Fig.1a) which reversibly stood applied biases between 100mV and 400mV. The measurements were done as a function of the magnetic field (H) up to 1000 Oe, applied along the easy (elliptic) axis and with four contacts method**.** We measured the voltage noise spectrum $S_V(f)$, using a cross-correlation technique [15], and in order to compare the noise level in different junctions, we use the phenomenological Hooge factor (α) which is determined from the relation: $S_v(f)=\alpha V^2/Af^\beta$, where A is the area of the sample, f is the frequency and V the bias voltage. Strictly speaking, the analysis of normalized noise using the phenomenological Hooge factor is valid only when the exponent β ranges between 0.7-1.3 [22]. Strong deviations from this dependence are usually caused by RTN, which has a Lorentzian power spectrum that is superimposed on the nearly 1/f noise power background [22].

Despite possible spatial fluctuations in the barrier thickness, which are unavoidable in MTJs with ultra thin barriers, following arguments rule out RTN explanation in terms of pinholes or “hot spots”: (i) large TMR close to expected for 0.9nm MgO barriers, (ii) robustness of the junctions to applied bias, including bias polarity and multiple field scans, and (iii) low average values of the normalized 1/f noise in the well define parallel (P) state ($3.1*10^{-11}$ μm^2), which are close to those expected from the empirical dependence of Hooge vs. R×A [23]. We note that few MTJs, with an area exceeding 0.0675 μm^2, revealed substantial TMR degradation, possibly due to pinhole formation already for bias of 100mV and the corresponding results thus are not presented here.

After 2-3 field sweeps between the antiparallel (AP) and P states, with rates of about 1 Oe/min most of the MTJs showed a noticeable decrease of the dispersion of the low frequency noise values vs. field accompanied by a small TMR increase of about 1-2%. These multiple field sweeps minimize fluctuations from metastable magnetic states and lead, for most of the MTJs, to two types of noise behavior depending on the junction area.

The smallest- medium (0.0245 μm^2 - 0.0503 μm^2) MTJs show a featureless AP state resistance with excess of 1/f noise, in accordance with previous reports for large-area MTJs with MgO barriers [16,17,23]. The low frequency noise in the P state, however, is different. Most of the smallest junctions reveal a huge enhancement of the noise in the P state (Fig.1b) which clearly has a RTN origin (further called RTN1). Interestingly, the anomalously strong increase of the noise power up to nearly 2 orders of magnitude (Fig.1b) is accompanied by a negligible change in the resistance of less than 0.2%. The RTN1 signal therefore comes neither from the free layer nor from part of the biased CoFeB layer interfacing the MgO barrier. Simple estimations show that changes of RTN1 with applied bias polarity (Fig.1b) could be partially attributed to self-field created by tunneling current.

In order to roughly estimate the effective fluctuating magnetic moment (Δm) we have measured the magnetic field and bias dependence of the ratio between inverse attempt transition rates [12,13]: $\tau_1/\tau_2 \sim \exp(-2\Delta mH/k_BT)$ with τ_1 and τ_2 being the average time spent in each of two thermally activated states. We note that the above simplified relation considers the magnetization directions of fluctuating states being P-AP to the external magnetic field. Figure 1c shows typical histograms corresponding to RTN1 with a magnetic field**,** indicated with arrows in Fig.1b**,** either above or below the maximum of noise in the P state. A linear fit of the $\ln(\tau_1/\tau_2)$ vs. H (Fig.1d) provides an estimation of the effective fluctuating moment of around $1.5*10^5$ μ_B and within 10% being independent of the bias polarity up to 400 mV. We estimate that fluctuating DW/MI occupy about 10% of the soft electrode area (with CoFeB effective moment per atom taken to be 1μ_B [24]). In order to account for 0.2% maximum variation of the resistance in the P state, close to the field interval, where RTN1 is activated (Fig.1b). The DW/MI to be activating by RTN1 should be located in the hard layer *outside* the MTJ stack. The possible origin of RTN1 is thus discussed further below.

The largest submicron MTJs (A=0.0565μm^2, 0.0675μm^2) do not show appreciable noise anomalies in the P state but reveal (Fig.3a) a strong noise enhancement in the AP state at least 100 Oe above the AP-P transition, also originated from RTN (further RTN2). Similar to RTN1, the investigation of the RTN2 time series as a function of magnetic field close to the maximum of the noise provides an evaluation of the fluctuating magnetic moment of about $4*10^5$ μ_B. A qualitatively new feature of the RTN2 instabilities is their pronounced dependence on the applied bias: RTN2 exists only with positive bias corresponding to the injection of electrons from the hard to the soft electrode (Fig.2a,b). Simple estimations indicate that the magnetic inhomogeneities which originate RTN2 are most probably located in the magnetically free electrode. Indeed, in this scenario the fluctuating relative area of the soft electrode is about 7% which is in rough agreement with the experimentally observed 2% reduction of TMR in the AP state (Fig.2a).

The absence of RTN2 for negative biases indicates the influence of spin torque transfer on the stability of fluctuating DW/MI. Indeed, if the positive bias favors the P alignment at large current densities through the spin torque effect, it will destabilize the AP alignment, while the negative bias direction would favor an AP alignment of the free and biased electrode and suppress RTN2. In contrast to RTN1, fluctuations similar to RTN2 were seen before in GMR nanopillars [25-27], but at extremely high current densities (exceeding 10^7 A/cm^2).

As soon as estimation with uniformly distributed current provides self-fields of few hundred of Oe for GMR nanopillars [26] this scenario should be also considered for our MTJs. As we mentioned above, self-field might explain bias asymmetry of RTN1 in MTJs with smallest area (Fig.1b). In order to verify similar scenario for the largest MTJs, Fig.3a compares dependence of the soft layer coercive field (H_c), characteristic field where resistance steps and RTN2 in the AP states are observed (H_{RTN2}) and estimated self-field $H_{self\text{-}field}$ (all referenced to zero current values) as a function of the applied current density. This analysis rules out significant influence of self-field on the asymmetric bias dependence of TMR steps and related RTN2 in the AP state (Fig.2). In addition, Fig.3(b-d) further checks for the effects of self fields on RTN2 by changing bias conditions near the noise peak. In order to compensate changes related to current with estimated variation of self-field below 2 Oe one should vary external magnetic field in about 30 Oe.

A simple model qualitatively explains the possible origin of the RTN (1,2) noise in the AP and P states and the strong asymmetry of the RTN2 with bias (Fig.4): while the soft elliptic electrodes in the smallest MTJs remain nearly in a single domain state, close to magnetization inversion, the largest electrodes show for the same magnetic fields (independently of the magnetic anisotropy [28] as confirmed by simulations) already a clear DW/MI formation with a 7% reduction of the magnetization of the soft layer (see Fig.4b), which could give rise to RTN2. Formation of the small (10^5 μ_B) DW/MI2 in the AP state may produce some impact on the current distribution (which is mainly of Δ_5 symmetry for the ideal AP alignment [1, 2]) creating a local "pseudo-pinhole" for electrons with Δ_1 symmetry with current partially redirected (as sketched in Fig.4a) into the DW/MI2 region where the AP alignment is disturbed. This concentration of the spin current into the DW/MI2 of "topological" origin, in combination with the presence of large perpendicular spin torque in MgO based MTJs [7], could explain, the influence of spin current on RTN2 already at relatively small (total) current densities, below 10^6 A/cm^2, which are at least a factor of 10 smaller than reported for GMR nanopillars [25-27].

The RTN1 observed in the smallest MTJs is most probably due to DW/MI1 located in the biased layer (due to their negligible contribution to TMR) outside and close to the edge of the MTJ pillar as sketched in Fig.4a. The origin of these DW/MI1 structures could be 360^0 DWs propagating through from the bottom SAF layer [29] and pinned, close to the edge, by the stray field of the soft Py elliptic layer in the P configuration (see sketch in Fig.4a). As long as the tunneling current does not cross the

DW/MI1, spin torque has a negligible influence and RTN1 is observed for both bias polarities. Figure 4b summarizes the characteristic magnetic fields where robust and reproducible maxima of RTN(1,2) were observed. Finally we mention that the absence of RTN1 in the P state of the largest MTJs with reduced influence of the edge stray field (Fig.4b) contradicts explanation of the RTN1 due to defects in the MgO barrier influenced by an external field through a magnetostriction.

In summary, random telegraph noise measurements in elliptical submicron magnetic tunnel junctions with dimensions close to the transition to the single domain regime revealed the presence of single magnetic inhomogeneities in the soft and hard layers. RTN fluctuations in the antiparallel alignment are asymmetrically influenced by the spin current which could be used to displace domain walls in the soft layer in the AP state of MTJs using relatively low tunneling current densities [30].

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Figure captions

Figure 1 a) Normalized TMR vs. RA product. Dashed line is guide for the eyes. Closed dots indicate junctions for which robust noise measurements have been done.

(b) TMR (line) and normalized low frequency noise (points) in MTJ with area of $0.0245\mu m^2$ measured with two opposite current densities of $\pm 1.9*10^6$ A/cm^2. Arrows correspond to the fields for which time traces are presented in the part (c).

(c) Time series and corresponding histograms measured in two magnetic fields above and below of maximum in noise in the P state indicated by arrows in the Fig.1b.

(d) Logarithm of the relation between inverse attempt transition rates (as evaluated from corresponding histograms (see part (c)) as a function of magnetic field. Solid line is mean square fit.

Figure 2 (a) TMR (represent with line) and normalized low frequency noise (represented with points) in MTJ with area of $0.0675\mu m^2$ measured with two opposite current densities of $\pm 5.2*10^5$ A/cm^2.

(b) Comparative bias dependence of effective fluctuating moments obtained from RTN1 and RTN2.

Figure 3 (a) Estimated maximum self-field ($H_{self\text{-}field}$) in comparison with dependence of coercive field (H_c) of the soft layer, and characteristic field (H_{RTN2}) where resistance steps and RTN2 in the AP state are observed (both referenced to H_c at zero bias) as a function of applied current density. Parts (b-d) show that variation of RTN2 under change in bias current (with estimated change in self-field below 2 Oe) is roughly compensated by external magnetic field of 30 Oe.

Figure 4 (a) Sketch of MTJs with an upper soft elliptical electrode, MgO barrier and bottom magnetically hard layer. DW/MI inside hard and soft electrodes indicated as (1) and (2) respectively. Dotted lines inside MgO barrier indicate suggested partial nonuniformity of spin current in the AP state due to some spin current with Δ_1 symmetry into DW/MI2. Dashed line sketches stray field from elliptic soft dot which induces edge DW/MI1 in the hard layer.

(b) Characteristic magnetic fields of RTN(1,2) as a function of MTJs area. The inset shows the magnetic configuration, simulated with OOMMF [31], of the elliptical small (0.0245 μm^2 – left) and largest (0.0675 μm^2- right) soft elliptical electrodes. Both images are presented for field corresponding to 7% reduction of magnetization in the larger dot due to appearance of DW/MI2. The following parameters have been used: saturation magnetization of $1150*10^3$ A/m, exchange stiffness of $20*10^{-12}$ J/m and magnetization damping parameter of 0.01. Qualitatively similar results (not shown) were obtained in the presence of uniaxial anisotropy K_u=1990J/m^3 [28].