

## Very low $1/f$ noise at room temperature in fully epitaxial Fe/MgO/Fe magnetic tunnel junctions

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We report on room temperature  $1/f$  noise in fully epitaxial Fe (45 nm)/MgO (2.6 nm)/Fe (10 nm) magnetic tunnel junctions (MTJs) with and without carbon doping of the Fe/MgO bottom interface. We have found that the normalized noise (Hooge factor) asymmetry between parallel and antiparallel states may strongly depend on the applied bias and its polarity. Both types of MTJs exhibit record of low Hooge factors being at least one order of magnitude smaller than previously reported. © 2007 American Institute of Physics. [DOI: 10.1063/1.2822812]

Recent advances in spintronics are mainly related to progress in the understanding of tunneling magnetoresistance (TMR) phenomena.<sup>1-3</sup> The major step forward was taken a few years ago when, following predictions by the theory,<sup>4,5</sup> experimentalists demonstrated<sup>6-10</sup> coherent spin-dependent tunneling in single crystalline Fe(100)/MgO(100)/Fe(100) magnetic tunnel junctions (MTJs). This achievement opened ways to create devices with extremely high room temperature (RT) TMR exceeding 100%. The low frequency noise at RT, and especially the so-called  $1/f$  noise, determines the values of the signal to noise ratio for each of the magnetic states [parallel (P) versus antiparallel (AP)] of the junctions, and therefore is an important parameter to be optimized. It was recently found that in MTJs, the  $1/f$  noise in P and AP configurations is mainly due to defects inside the insulating barrier.<sup>11</sup> Previous studies of the  $1/f$  noise in MTJs with a MgO(111) barrier revealed a dependence of  $1/f$  noise on the magnetic alignment.<sup>12</sup> Similar effects were later reported for sputtered grown CoFeB/MgO(100)/CoFeB MTJs (Refs. 13 and 14) indicating that the low frequency noise in MTJs with a MgO barrier may not just be determined by the derivative of tunneling resistance with respect to the magnetic field.<sup>15</sup> The Fe/MgO/Fe MTJs are ideal devices to engineer the chemical and electronic structures of the Fe/MgO interface in order to manipulate the voltage variation of the TMR in amplitude and sign.<sup>10</sup>

This letter presents a *detailed study of  $1/f$  noise in fully epitaxial MTJs* with large RT-TMR (above 100%). We have investigated the normalized  $1/f$  noise (Hooge factor  $\alpha$ ) in Fe/MgO/Fe MTJs, with and without carbon doping of the Fe/MgO interface, as a function of magnetic configuration and applied bias up to 0.5 V. For carbon-doped MTJs the Hooge factor asymmetry,  $\alpha(\text{AP})/\alpha(\text{P})$ , may strongly depend not only on the bias but also on its polarity. *The normalized  $1/f$  noise for both types of the epitaxial MTJs shows low record values.*

Our epitaxial Fe (45 nm)/MgO (2.6 nm)/Fe (10 nm)/Co (20 nm)/Pd (10 nm)/Au (10 nm) samples were grown by molecular beam epitaxy on MgO(100) substrates

under UHV conditions ( $4.10^{-11}$  mbar base pressure). A complete review of the growth procedure can be found in Ref. 16. Two different sets of the samples were grown: with clean Fe/MgO bottom interfaces (B-MTJs) and with carbon doping (A-MTJs) at bottom Fe/MgO interface (Fe/Fe-C/MgO). The samples with carbon at the bottom Fe(001) electrode present an additional  $c(2 \times 2)$  surface reconstruction.<sup>16</sup> The reflection high energy electron diffraction patterns showed no clear evidence of any structural difference between the two systems. After the growth of the multilayer stack, MTJs with micrometric lateral size were patterned using standard optical lithography and ion etching processes. Tunneling magnetoresistance, dynamic conductance  $G(V)$ , and low frequency noise versus bias and magnetic field have been studied at 300 K using a four-probe method. The MTJs were biased using a constant dc current with a superimposed low amplitude square wave ( $V_{ac} < 10 \mu\text{A}$ ). The positive bias corresponds to electrons injected from the bottom to the top electrode. The voltage drop on the junctions and the current were obtained by using an analogue-digital converter which provides the dynamic conductance and the dc voltage. The noise measurements were performed using a cross-correlation technique. More details of the experimental setup were published in Refs. 12 and 17.

Figure 1 presents a typical voltage noise spectrum  $S_V(f)$  below 1 kHz in P and AP configurations for one of the MTJs with a low noise level. The white noise observed above 100 Hz in the P state is well accounted by the thermal and shot noise contributions. The low frequency part of the noise spectrum is clearly dominated by the so-called  $1/f$  noise (see the line drawn as a guide for the eyes). In the AP state, in the frequency range studied, the voltage noise typically consists of the  $1/f$  background superimposed by the additional noise contribution of Lorentzian type. In the following, we shall analyze the  $1/f$  contribution as normalized noise power by means of the widely used phenomenological Hooge parameter ( $\alpha$ ) defined as  $\alpha = fAS_V(f)/V^2$ , where  $A$  is the junction area and  $V$  is the dc voltage applied to the junction.<sup>18</sup> Figure 1(b) shows the typical dependence of the Hooge parameter on the magnetic field in A-MTJs for positive bias. A clearly visible excess of the normalized noise in the AP state is

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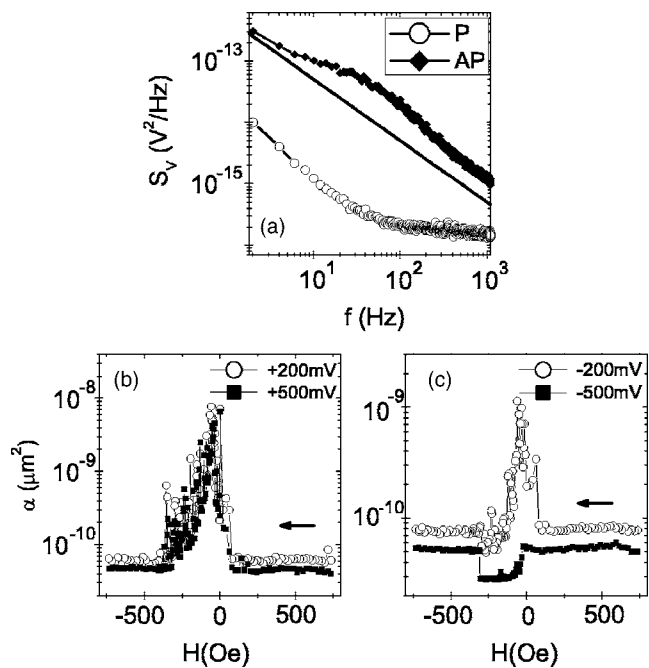


FIG. 1. (a) Typical noise spectrum measured in A-MTJs in the P and AP states with a positive bias of 200 mV. Field dependence of the normalized noise  $\alpha$  for (b) positive and (c) negative biases. The arrows show the direction of variation of the magnetic field.

observed for this bias polarity. A similar feature has been found in other MTJs with MgO barrier<sup>12,13</sup> and has no direct link to the derivative of the resistance with respect to the magnetic field. This means that the noise variation between the P and AP states is not due to magnetic domains or other magnetic inhomogeneities. We have observed that the noise asymmetry is independent on bias polarity in the B-MTJs. However, in the A-MTJs, where the TMR may be inverted for one of the bias polarities, an interesting behavior of the noise asymmetry versus bias with normalized noise in the P state exceeding the one in the AP state [Fig. 1(c)] has been measured for negative voltages exceeding  $-300$  mV.

Most of the B-MTJs showed an increase of the normalized voltage noise for applied biases exceeding 200 mV (not shown). For some of the B-MTJs, the noise enhancement with increasing bias could even become irreversible. The increase of the voltage noise was huge (up to few orders of magnitude) once bias above 200 mV had been applied, and was accompanied by some reduction (down to 120%) in the TMR. We explain this by the strong sensitivity of the defects distribution in the B-MTJs to an applied electric field exceeding  $10^6$  V/cm. The A-MTJs showed, however, the normalized  $1/f$  noise decreasing with increasing applied voltage up to at least 500 mV [Fig. 2(a)]. This dependence, as is evidenced in Figs. 1(b) and 1(c), is rather asymmetric being the inversion of the noise asymmetry linked to the TMR inversion point (see vertical dotted line in Fig. 2.) We note that, in general, for the A-MTJs, both conductance and  $1/f$  noise level appeared to be much more stable to the applied external electric field above  $10^6$  V/cm, in agreement with our recent findings for carbon-doped epitaxial Fe/MgO/Fe with larger MgO barriers.<sup>19</sup>

It may be seen that the normalized noise dispersion in the AP state decreases rapidly when applying negative biases of a magnitude above the TMR inversion [Fig. 2(b)], while for the P configuration, the noise dispersion is almost inde-

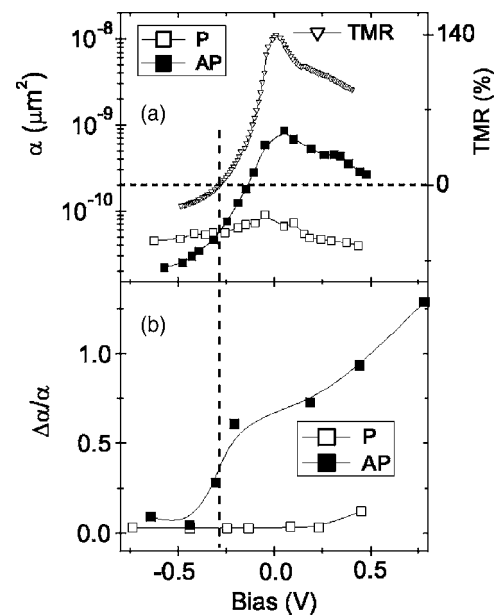


FIG. 2. (a) Bias dependence of the Hooke parameter in the P and AP states in the A-MTJs, evaluated for the frequency range of 2–20 Hz (left axis), and TMR vs bias (right axis). (b) Bias dependence of the normalized dispersion of the Hooke parameter  $\Delta\alpha/\alpha = \sqrt{\langle(\alpha - \langle\alpha\rangle)^2\rangle} / \langle\alpha\rangle$  in the AP and P states of the A-MTJs evaluated outside the transition regions between P and AP configurations.

pendent of bias. This unexpected behavior could be a consequence of a strong enhancement of the AP conductance once the applied bias exceeds  $-300$  mV. In our view, the observed strong suppression of the normalized “noise of the noise”<sup>18</sup> arises from a transition between the regime where the noise in the AP conductance is mainly controlled by the defects inside the barrier to the one in which the AP conductance and its noise are determined by the resonant electrons tunneling to interface localized states, contributing to opening of the new conductance channels at negative biases exceeding  $-300$  mV.

Figure 3 resumes electron conductance (part b) and noise (part a) data obtained for 13 MTJs (seven of the type A and six of the type B). Both types of MTJs show rather low dispersion in the TMR values, being  $157 \pm 7\%$  for B-MTJs and  $152 \pm 16\%$  for A-MTJs. Interestingly, carbon doping does not substantially influence the resistance by area (RA) product which was observed to be  $40 \pm 8$  k $\Omega$   $\mu\text{m}^2$  for B-MTJs and  $38 \pm 4$  k $\Omega$   $\mu\text{m}^2$  for A-MTJs. These values of the TMR and conductance are rather close to those reported previously for fully epitaxial Fe/MgO/Fe MTJs with similar MgO barrier thickness.<sup>9,16</sup>

Our most important finding is that the normalized noise for both A- and B-MTJs studied may be notably (about one order of magnitude) smaller than the best previously reported levels in MTJs with MgO barriers, which were measured at similar biases and were characterized by somewhat larger RA ratios.<sup>14</sup> Furthermore, the smallest P-state Hooke factors observed here ( $\alpha \approx 10^{-11}$   $\mu\text{m}^2$ ) are at least one order of magnitude smaller than the smallest Hooke factors ever reported for MTJs with different barriers and with RA products within the wide range between  $10^{-4}$  and  $10^3$  M $\Omega$   $\mu\text{m}^2$  (see dotted line in Fig. 3 obtained from the analysis made in Ref. 13).

The observed very low  $1/f$  noise in fully epitaxial Fe (45 nm)/MgO (2.6 nm)/Fe (10 nm) MTJs with or without carbon doping of the Fe/MgO interface seems to be related

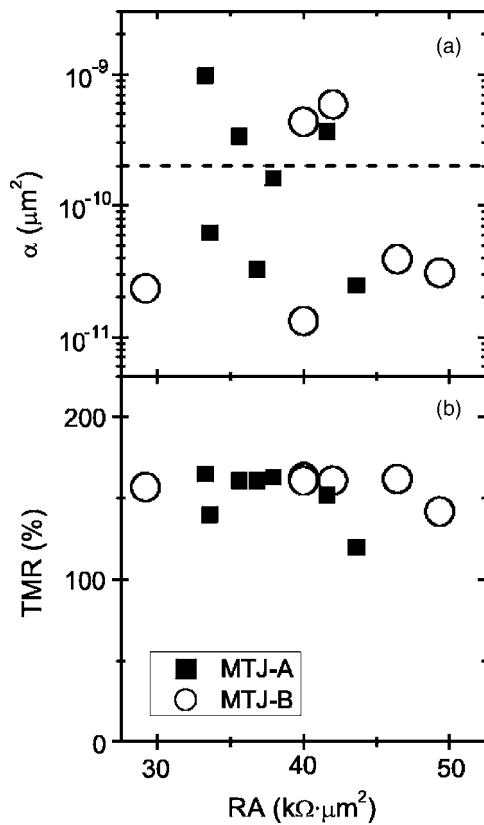


FIG. 3. Normalized noise measured at +200 mV (a) and zero-bias TMR (b) as a function of RA product. The dashed line (part a) indicates the lowest Hooqe factor value previously reported for MTJs with RA product within the wide range between  $10^{-4}$  and  $10^3 \text{ M}\Omega \mu\text{m}^2$  (see Ref. 13).

to a much higher degree of epitaxy of the MgO barrier in comparison with quasiepitaxial MTJs with MgO barrier studied before. In addition, the carbon doping, through the  $c(2 \times 2)$  reconstruction,<sup>16</sup> could partially relax stress at the Fe/MgO interface, remove defects out of MgO and create the enhanced robustness of the MgO barrier to applied electric field.

In conclusion, we have found very low values of the room temperature  $1/f$  noise in fully epitaxial Fe/MgO/Fe magnetic tunnel junctions. The TMR inversion observed in A-MTJs is accompanied by an inversion of the Hooqe factor asymmetry between the P and AP states. These results show a great potential for integration of the fully epitaxial MTJs into spintronic devices.

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