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Low frequency noise in $Co/Al_2O_3\langle\delta(Fe)\rangle/Ni_{80}Fe_{20}$ magnetic tunnel junctions

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Abstract
The time dependences, up to 200 s, and the noise power spectrum (0.005–10 Hz) in the electron transport response at bias up to 300 mV of $Co/Al_2O_3/Ni_{80}Fe_{20}$ magnetic tunnel junctions (MTJs) and of $Co/Al_2O_3\langle\delta(Fe)\rangle/Ni_{80}Fe_{20}$ (with Fe δ dopants of thickness 1.8 Å inside the barrier) were investigated. The magnetic field was changed between +100 and −100 G in steps of 1 G. The measurements were carried out at different temperatures between 77 and 300 K for the samples with large tunnel magnetoresistance (exceeding 14% at 300 K). We found that the magnetization reversal of the Co and permalloy electrodes, as detected from the time response near the coercive field, occurs via relaxation on the timescale of about 10^2 s with sudden jumps in the resistance ($\Delta R/R \sim 10^{-2}$–10^{-3}). We link this noise to the depinning of the domain walls. In addition to the magnetic noise, in some of the studied MTJs with Fe δ dopants, we observed a two-level-system telegraph-type noise, which was independent of the magnetic field, indicating its relation to the trapped charges inside the insulating barrier. For MTJs, the noise power spectrum has $1/f^\alpha$ character for a wide frequency range below a few Hz. At low bias and parallel state the exponent α is close to 1–1.5, but at higher bias or in the antiparallel state the exponent increases to 2. We link these effects to non-equilibrium noise in magnetic structure of the electrodes in the antiparallel state and to non-equilibrium transport inside the barrier at high bias.

1. Introduction

Magnetic tunnel junctions (MTJs) exhibit a large magnetoresistance at low field and only a narrow range of fields is needed to switch them. These properties make MTJs good candidates for non-volatile memory and magnetic field sensors. It was recently found that the main characteristic of MTJs strongly depend on quality, type of the barrier, interfaces as well as on the applied bias. Till now the main information about junctions has been obtained through direct study of transport characteristics such as resistance vs magnetic field (TMR) and current–voltage characteristics (IV) [1], but little is known about the character of noise in these structures. Most of the literature on the noise power spectrum in MTJs is related to antiferromagnetically biased junctions at frequencies above a few Hz [3–5]. Our work presents a detailed study of the noise in MTJs of $Co/Al_2O_3\langle\delta(Fe)\rangle/Ni_{80}Fe_{20}$ with the thickness of the delta layer up to 1.8 Å. In this paper, we mainly concentrate on the results obtained for undoped MTJs. Detailed comparison of the noise in doped vs undoped samples will be given in forthcoming publications. The temperature was varied between 300 and 77 K, junction voltage up to 0.3 V, applied magnetic field between +100 and −100 G, and frequency range of interest was below a few Hz.

2. Experimental procedures

Details of sample preparation was previously described in [1, 2]. In brief, a 1 nm seed layer is deposited on a glass substrate at 77 K. Then, cobalt (8 nm) (hard layer) and aluminium (depending on the samples, the thickness of Al was varied between 0.6 and 1 nm) layers were deposited at the same temperature. At the next stage, the samples were warmed to room temperature and oxidation of the barrier was produced by glow discharge, followed by deposition of a permalloy layer (10 nm) (soft layer). In the following, this type of sample will be named as 'control'. When a Fe δ layer was included into the barrier, a 0.7 nm layer of aluminium was first deposited on top of the cobalt electrode followed by iron of thickness δ and then followed again by another aluminium layer with the same (0.7 nm) thickness. The oxidation process was similar to the one used for control junctions, resulting in a layer of oxidized Fe between the layers of Al_2O_3, although the existence of isolated ions and/or clusters of iron ions is not discarded. All junctions had a cross section of $200\,\mu m \times 200\,\mu m$, defined by additional Al_2O_3 film. During deposition of the magnetic electrodes, a magnetic field of about 50 G was applied along the Co stripe providing an uniaxial anisotropy along the same direction for both electrodes. Inclusion of iron in the barrier does not affect the coercive field of the studied samples within 10%.

Before the measurements, all MTJs were saturated to a ferromagnetic (FM) state by an applied magnetic field of 100 G along the easy axis. The noise was studied in a four-probe geometry with a dc current and with the magnetic field changing in steps of 1 G. Magnetic field was created by a solenoid fed by a source with a stability better than 10^{-4}. The upper limits for the variation of the signal due to the source instability are indicated by the error bars in figures 1(*c*) and (*d*). After each field step, the relative response of the system $\delta V = V(\text{time}) - V(0)$ was measured as a function of time each 0.1–0.4 s up to $t \sim 100$–200 s by using a nanovoltmeter, Keithley2182. In order to obtain the noise power spectrum (S) as a function of frequency (f), the time series were analysed by a fast Fourier transform (FFT) procedure. Finally, before the field was changed, the measurement of the resistance of the sample was carried out. In separate experiments, the IV curves as well as the usual TMR characteristics were also determined. The quality of the barrier was tested by using the method proposed in [6]. Both the high TMR (about 20%), the temperature dependence of TMR (resistance increases on cooling from 300 to 77 K, see figure 1(*a*)) and the IV characteristics with gap indicate excellent MTJs without pinholes.

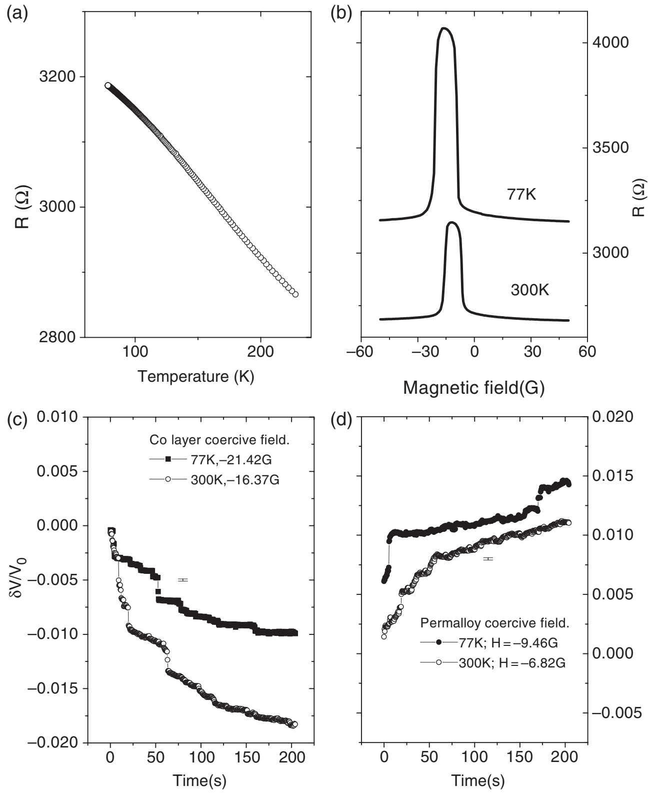

Figure 1. (*a*) Typical temperature dependence of the resistance of MTJs and (*b*) magnetoresistance of undoped MTJ at 300 and 77 K. (*c*) and (*d*) show behaviour of normalized δV vs time at 77 and 300 K for magnetic fields close to the Co (*c*) and permalloy (*d*) coercive field ($\Delta(\delta V/V_0) \sim 10^{-6}$).

3. Results and discussion

Both for permalloy ($Ni_{20}Fe_{80}$) and Co layers, the time response near coercive field does not show logarithmic or exponential relaxation and is strongly affected by domain wall (DW) depinning processes. In permalloy, these phenomena (i.e. DW jumps) occur on the timescale about 1–2 s for temperatures between 300 and 77 K. Apparently, depinning of Co DWs occurs faster than in 0.2 s and looks more like 'Barkhausen noise'. Figure 1(*b*) presents magnetoresistance at 77 and 300 K, while figures 1(*c*) and (*d*) show typical time response series near coercive field H_C of Co (*c*) and permalloy (*d*). We note that at room temperature, H_C ($Ni_{20}Fe_{80}$) is 5 G and H_C (Co) is about 15 G. Clearly, the switching in the electrodes is not instantaneous and is composed of both slow and fast relaxation regions which reflect delay in the reaction of the magnetic domain structure. Surprisingly, the relaxation process can take up to few minutes, until a new equilibrium domain configuration for the particular magnetic field is reached.

Figure 2 demonstrates the influence of the iron δ layer on the noise and TMR. Apparently, inclusion of Fe in the barrier improves TMR. Effect of dopants inside the barrier was studied by one of us in [2]. It was found [2] that inclusion of Ni and Si decrease TMR due to spin flip scattering in the case of Ni and due to defect states in the barrier which could open new conduction channels. However, in our case the effect of barrier doping is different and remains unexplained until now. Further work is needed in order to clarify this issue. For intermediate doping level, presence of the Fe layer inside the barrier strongly increases the relative noise amplitude (see figure 2). Surprisingly, for $\delta = 0.12$ nm iron doped samples, we found a strong two-level system (TLS) type noise which remains practically unchanged when a magnetic field up to 100 G is applied. This fact points out that these TLSs are not related to a magnetic degree of freedom but probably originate from non-magnetic structural defects at interfaces, caused by deposition of the Fe layer.

Another important result of this paper, which has been obtained for undoped MTJs (down to 77 K) and at 300 K for

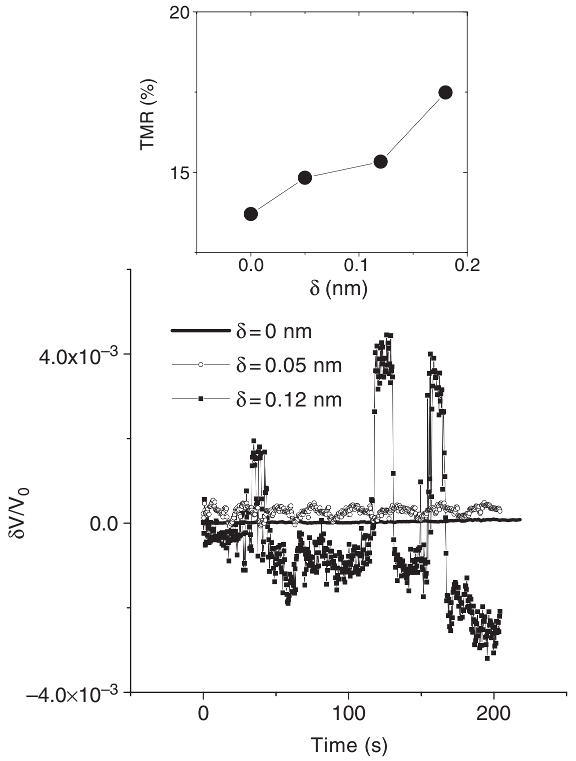

Figure 2. Time series taken at room temperature and in field far from coercive field (~35 G) for samples with different thickness of the Fe interlayer inside the barrier. Inset shows the dependence of TMR on iron layer thickness δ (see text for details).

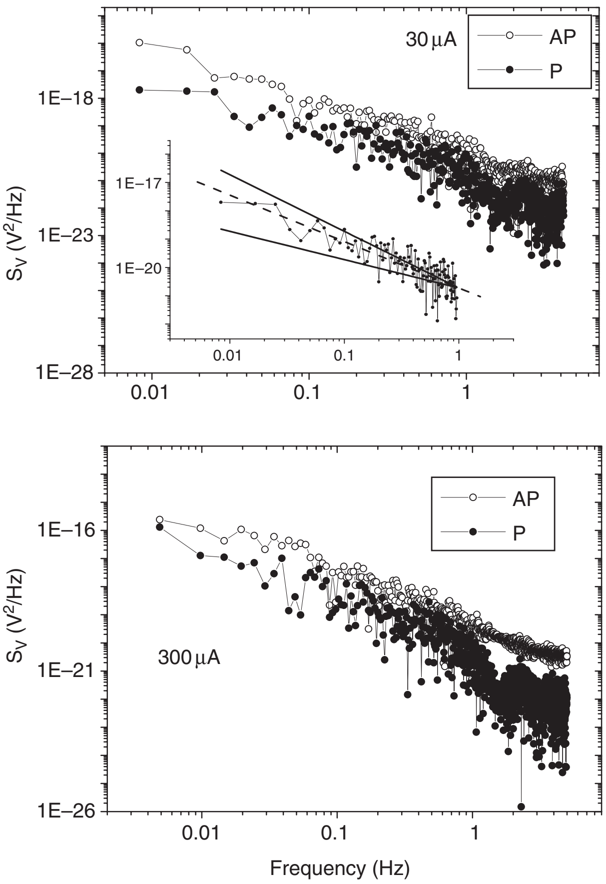

Figure 3. Typical noise power spectrum obtained from undoped MTJ at 300 K for 30 μA bias current (upper graph) and 300 μA (bottom graph) plotted in a log–log scale. Inset shows the limiting cases for the exponents (1–2).

doped ($\delta = 0.18$ nm) MTJs, is related to the transformation of the noise power spectrum with applied voltage (see figures 3–5). Figure 3, which in log–log scale shows $S(f)$ for undoped (control) MTJ, indicates that at low frequencies ($f < 1$ Hz) the noise power spectrum is proportional to $1/f^{\alpha}$. At low bias ($I \lesssim 50\,\mu$A), the exponent α is near to 1 for the parallel (FM) configuration. This implies that the tunnel junctions, which are not affected by the magnetic noise, show a typical $1/f$ noise power spectrum. Such behaviour could be explained with the Dutta–Dymon–Horn approximation by the charge trapping processes in the barrier [7]. Frequency dependence of the noise power spectrum dramatically changes in the antiparallel state and at high applied bias, where S is also linear in log–log scale, however with the exponent α increased to about 1.5–2. Figure 4 summarizes the results obtained for three different temperatures. At small bias, the exponent α obtained for the antiparallel state tends to increase with temperature. The corresponding behaviour is found to be different when iron is introduced inside the barrier (figure 5). One sees that the dependence of the exponent α on the bias becomes weaker. However, similarly to undoped MTJs, the exponent of the noise power spectrum in the antiparallel configuration ($\alpha \sim 2$) remains bigger than in the parallel configuration ($\alpha \sim 1.5$).

To our best knowledge, the only theory which actually explains the noise power spectrum proportional to $1/f^{\alpha}$ with the exponent α of about 1.7 is the one which considers the effect of avalanches (i.e. Barkhausen noise) on a magnetic noise power spectrum [8]. Indeed, this model could explain the

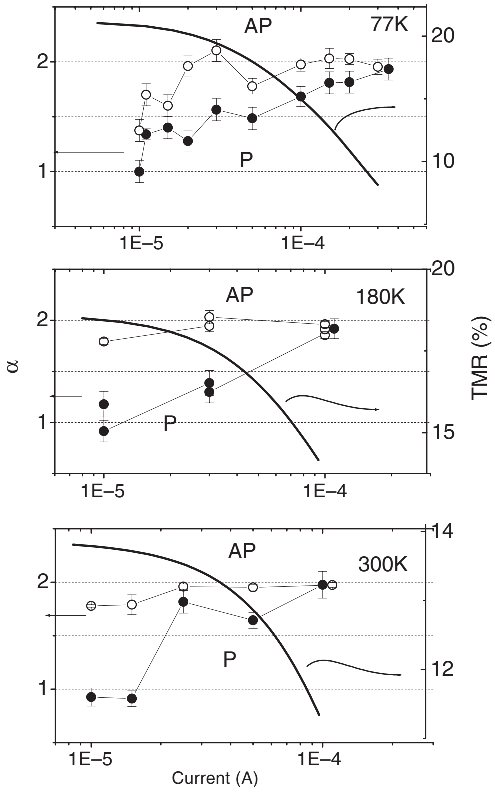

Figure 4. Exponent α (left axis) and TMR (right axis) for undoped MTJ at different temperatures as a function of bias current. Open points correspond to the antiparallel (AP) state and closed to the parallel (P) state. Error bars are standard deviations obtained in the fit.

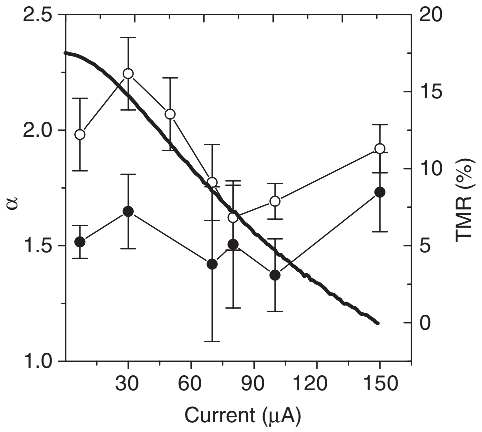

Figure 5. Exponent α (left axis) and TMR (right axis) for doped MTJ ($\delta = 0.18$ nm) at room temperature as a function of bias current. Open points correspond to the antiparallel (AP) state and closed to the parallel (P) state. Error bars are standard deviations obtained in the fit.

results obtained for the antiparallel state where the magnetic structure is unstable and the tunnel current reflects this instability. An enhanced exponent ($\alpha \sim 2$) obtained for the parallel state at high bias or when iron is included could reflect non-equilibrium tunnelling through the barrier caused by modification of the properties of the aluminium oxide density of states, either by the bias or the impurity states introduced by the dopants. Verification of these possibilities, however, calls for additional experiments.

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