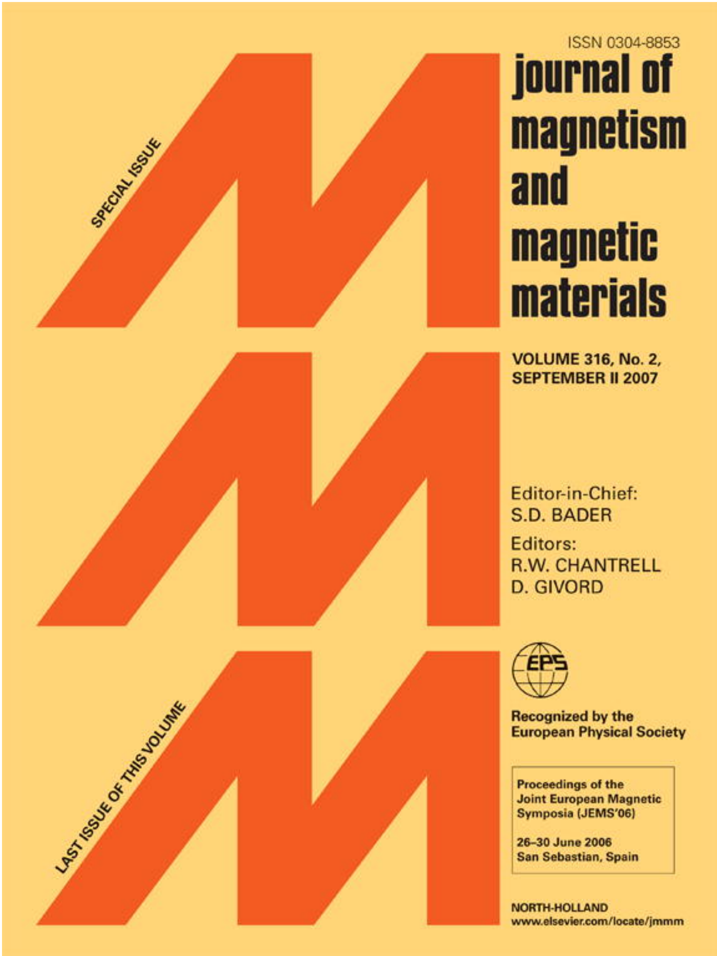
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Shot noise in $Co/Al_2O_3\langle M\rangle/Py$ (M = Cr, Si) magnetic tunnel junctions

R. Guerrero[a], F.G. Aliev[a,*], T. Santos[b], J.S. Moodera[b]

[a]Departamento de Física de la Materia Condensada, C-III, Universidad Autónoma de Madrid, Cantoblanco, 28049 Madrid, Spain
[b]Massachusetts Institute of Technology, Cambridge, MA 02139, USA

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Abstract

Low-frequency noise, including $1/f$ and shot noise (SN), and dynamic tunneling resistance have been studied in Co (80 Å)/Al_2O_3 (14 Å)/Py (100 Å) magnetic tunnel junctions (MTJs) without doping and with Cr or Si δ-doping of the insulating barrier. The fluctuations in voltage were measured at frequencies ($200<f<2000$ Hz), temperatures below 10 K and biases under 150 mV. For the undoped MTJs with the smallest ($<10\,k\Omega$) and the highest ($>100\,k\Omega$) tunneling resistances, the Fano factor shows "full" SN corresponding to uncorrelated tunneling ($F=1$). The SN is reduced for the intermediate resistances with $F\approx 0.65$–0.8 indicating correlated electron tunneling, most probably through the localized states formed by the defects inside the barrier. The SN is enhanced for the antiparallel alignment of the ferromagnetic electrodes in the MTJs with tunneling weakly affected by spin-flip scattering. A model, which considers trap-assisted sequential tunneling, qualitatively explains the main experimental results. Cr-doped MTJs typically showed Fano factor close to unity, probably due to some growth condition-induced asymmetry in Cr distribution. Incorporation of a Si δ-layer permits observation of an enhancement of the low-frequency noise, probably induced by Coulomb blockade effects.

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Keywords: Shot noise; Sequential tunneling; Magnetic tunnel junction

1. Introduction

Observation of large tunneling magnetoresistance (TMR) at room temperature in magnetic tunnel junctions (MTJs) [1–3] has boosted interest in the spin-dependent tunneling phenomena [4,5]. MTJs with tunneling resistance (TR) depending on the relative orientation of magnetic layers are attractive candidates for sensors and magnetic storage technology. In order to improve the detection sensitivity of MTJs, one should increase TMR and minimize the noise, particularly $1/f$, thermal and shot noise (SN). While the thermal noise in equilibrium is related to linear response resistance, the SN is a consequence of the discreteness of the electronic charge flowing through the structure out of equilibrium and contains information not accessible from time-independent conductance. In the absence of correlations, the noise power (S) is characterized by its limiting ($f\to 0$) value $S=2eI$ (e, electron charge and I, average current). The Fano factor $F=S/2eI$ represents normalized SN. The way to influence SN is to induce electron correlations between tunneling electrons. Correlations may affect both TMR and SN [6–8]. The only study on the low-frequency SN in magnetoelectronic devices by Nowak et al. [9] reported on observation of "full" SN ($F=1$) in MTJs with antiparallel (AP) alignment of the electrodes. This paper reports on the first systematic measurements of both TMR and SN in MTJs without and with doping the barrier. For the MTJs with the smallest and the highest tunneling resistances, the Fano factor shows an uncorrelated tunneling ($F=1$). The SN is reduced for the intermediate resistances with $F\approx 0.65$–0.8 indicating correlated electron tunneling, most probably through the localized states formed by the defects inside the barrier. The SN is enhanced for the antiparallel alignment of the ferromagnetic electrodes in the MTJs with tunneling weakly affected by spin-flip scattering. Incorporation of a Si δ-layer permits observation of an enhancement of low-

*Corresponding author. Fax: +34 91 4973961.
E-mail address: farkhad.aliev@uam.es (F.G. Aliev).

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frequency noise, probably induced by Coulomb blockade effects.

2. Experimental

Noise is measured in a set-up described in Ref. [10], which employs the cross-correlation method. Computer control of the current through the sample permits the measurement of the noise and dynamic tunneling resistance as a function of bias current at fixed magnetic fields and conversion of the voltage noise in the current noise. The current flowing through the sample is converted into voltage by an I–V converter and is analyzed either by a DC voltmeter or by a lock-in amplifier to measure the bias voltage and the dynamic conductance, respectively. The voltage from MTJs is measured by two identical home-made DC-coupled ultra low-noise amplifiers, placed in the top part of the cryostat. The pre-amplified signals are further amplified by other low-noise amplifiers (SR560). A spectrum analyzer SR780 calculates the cross-correlation spectrum containing thermal, shot and $1/f$ contribution to the noise. This technique removes uncorrelated noise from the amplifiers and the noise of the leads. The influence of the capacitance of the line (about 400 pF) and of the MJTs (about 10 nF) as well as their resistance (10–600 kΩ) is taken into account during noise analyses without using fitting parameters. The SN was measured for 12 MTJs: four without doping, six with Cr doping ranging between 0.4 and 1.2 Å and total noise V_{rms}—for MTJ with asymmetric Si δ-doping (1.8 Å).

3. Results and discussion

Fig. 1 shows typical electron-transport characteristics of the studied MTJs. The dynamic tunneling resistance vs. bias (V) measured at three temperatures for parallel alignment proves pinhole-free MTJs. For all MTJs studied, a zero-bias anomaly (ZBA) appeared below $T \sim 77$ K.

The general view of the ZBA is that finite temperature and bias allow for some inelastic-scattering processes coupled to tunneling events, opening additional transport channels. Presently, there exist several possible explanations of the ZBAs in MTJs [11–14], which consider magnon- or phonon-assisted tunneling or two-step tunneling through impurities inside the tunnel barrier, which are also coupled to some additional degrees of freedom. Such processes require hot electrons, leading to the low-bias/temperature suppression of the conductance. Estimation of the barrier height and thickness (Fig. 2) demonstrates nearly uniform Al_2O_3 barrier parameters. It was made for four undoped and five Cr-doped MTJs, by using parabolic fits of the I–V curves [4] at low bias ($V < 200$ mV) for both parallel (P) and antiparallel (AP) magnetic configurations.

Doping of the barrier with Cr generally suppresses both the TMR and the conductivity, but the relations between these parameters and the nominal Cr concentration are not strictly monotonic. We have found, however, that the changes in the TMR are correlated with those of the junction resistance R_J. The TMR is also monotonically reduced with the applied voltage both for the Cr-free and Cr-doped MTJs, in accordance with previous reports [11,12]. The monotonic suppression of the TMR and TR with bias indicates that we do not have Kondo impurities in the strong-coupling regime (at least down to the lowest temperature $T = 2$ K), where tunneling resistance decreases at T, $V \to 0$ due to the Kondo resonance.

Fig. 3a shows a typical voltage noise for the frequency and bias range where the $1/f$ noise does not affect the data and the applied bias ($eV \gg k_B T$) ensuring that SN presents the dominant contribution to the total noise. Fig. 3b shows a typical dependence of the Fano factor on bias voltage. For most of the undoped MTJs, the Fano factor was reduced below the Poissonian value ($F < 1$), while for the Cr-doped MTJs the Fano factor was always close to 1.

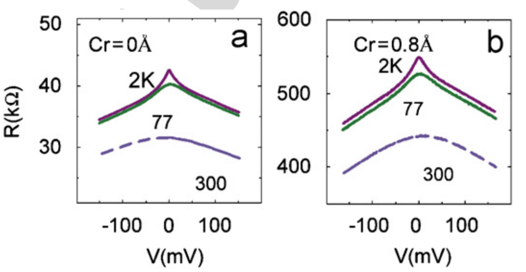

Fig. 1. Dynamic resistance vs. bias for undoped (a) and doped (b) MTJs measured between 2 and 300 K.

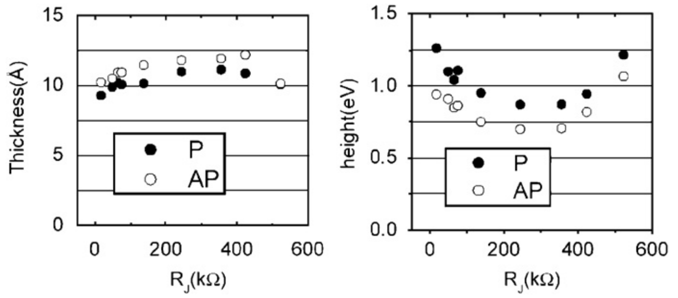

Fig. 2. Estimated thickness and barrier height for $Co/Al_2O_3\langle Cr\rangle/Py$ MTJs. Resistance range separating doped and undoped junctions is shown in Fig. 4.

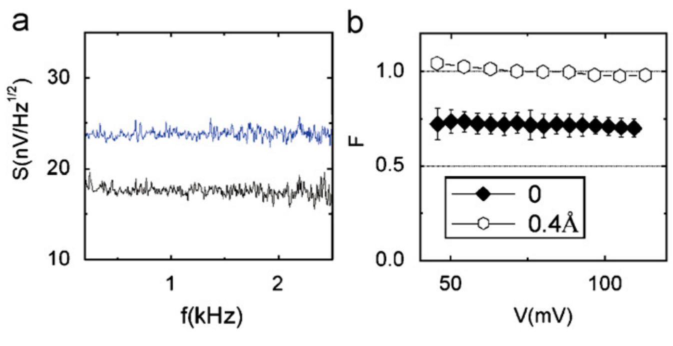

Fig. 3. Typical shot noise for currents of 3 and 6 μA (a) and dependence of the Fano factor on applied bias (b) for two different MTJs measured at 2 K.

Fig. 4 shows the TMR and Fano factor for the parallel alignment as a function of the R_J at $T = 2$ K. The Fano factor was averaged over the range 40–120 mV where it is nearly bias independent. For the undoped MTJs in the range where TMR is only weakly reduced with the R_J (< 100 kΩ), we observed a gradual suppression of the Fano factor down to $F\sim0.65$. Doping of the barrier with Cr further increases the tunneling resistance and restores the Poissonian SN ($F\sim1$). Surprisingly, we found that the Fano factor depends on the alignment of the electrodes with $F_{AP}/F_P > 1$ only in the MTJs with a weak ZBA and becomes nearly independent of the alignment above some threshold value of the ZBA [15].

Fig. 5 presents preliminary results on the noise and dynamical conductance for Co/Al_2O_3⟨Si⟩/Py MTJs with an asymmetrically situated Si δ-layer of 1.8 Å. We observe an enhancement of the total noise (V_{rms}, bandwidth of 6.4 kHz) with a threshold of 30 mV and strongly asymmetric bias dependence. The enhancement of V_{rms} is due to random telegraph noise (RTN). The dynamical conductance measurements reveal a strong ZBA, which does not saturate up to 200 mV (inset in Fig. 5). These features were not observed for the undoped MTJs. We tentatively explain this behavior as due to sequential tunneling, which is suppressed by Coulomb blockade below a critical Si thickness. For the thickest Si layers, two-step tunneling is allowed, yielding enhanced ZBA. The RTN is possibly due to the movement of charged defects, changing the electrostatic environment (capacitance) and affecting in this way the two-step conductance [18]. Further work is planned to confirm this scenario.

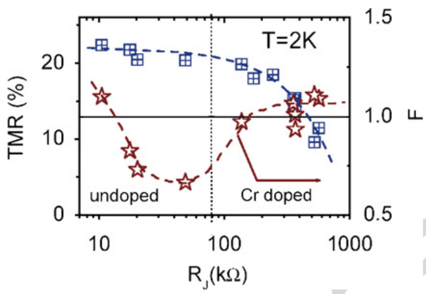

Fig. 4. Dependence of TMR and Fano factor on tunneling resistance for undoped and Cr-doped MTJs.

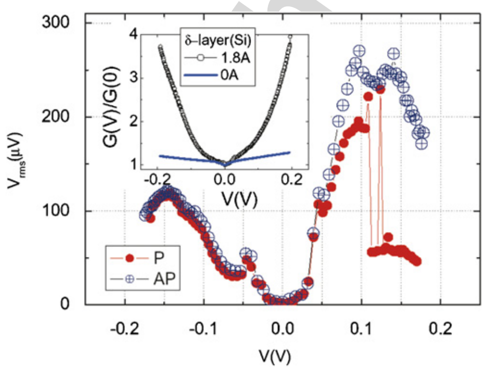

Fig. 5. Bias dependence of the V_{rms} and the normalized conductance in the P state (inset) measured at 2 K for MTJs with Si δ-doped (1.8 Å) layer inserted asymmetrically. Inset shows the normalized conductance of the doped and undoped samples.

Previous studies of the SN in non-MTJs found that for sequential tunneling predominantly through impurities in the middle of the barrier, the Fano factor can be reduced below unity [16] even for randomly distributed impurities within the barrier, as the current is dominated by hopping through the center. Theory shows that Fano factor for tunneling through uniformly distributed point-like localized states is in general $F = 3/4$ [17] (in the absence of hopping correlations between the two spin species). The Fano factor is reduced (Fig. 4) as the tunnel barrier becomes wider and the role of the two-step tunneling processes become relatively more important. Enhancement of the noise to roughly Poissonian level after Cr doping could be due to some offset in Cr deposited nominally in the center of the junction, which leads to systematically asymmetric hopping. The observed correlation in the AP–P Fano factor asymmetry and the ZBA [15] suggest that an inelastic spin-flip mechanism in the barrier is responsible for concurrent reduction of the former and enhancement of the latter.

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