phys. stat. sol. (a) **205**, No. 5, 1040–1042 (2008) / **DOI** 10.1002/pssa.200776455

physica status solidi a
www.pss-a.com
applications and materials science

Low frequency noise in $Co/Al_2O_3\langle Si\rangle/Py$ magnetic tunnel junctions

R. Guerrero[1], **F. G. Aliev**[*, 1], **R. Villar**[1], **T. Santos**[2], and **J. Moodera**[2]

[1] Dpto. de Física de la Materia Condensada, C-III, and Instituto "Nicolás Cabrera" de Ciencia de Materiales, Universidad Autónoma de Madrid, 28049 Madrid, Spain

[2] Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, Boston, USA

Received 5 July 2007, accepted 7 January 2008
Published online 23 April 2008

PACS 72.25.–b, 73.40.Gk, 73.50.Td, 75.47.–m

[*] Corresponding author: e-mail farkhad.aliev@uam.es, Phone: +34 91 497 8596, Fax: +34 91 497 3961

Low frequency noise and dynamic tunneling resistance have been studied in Co(80 Å)/Al_2O_3(12 Å)/Py(100 Å) magnetic tunnel junctions (MTJs) with and without asymmetric Si doping of the insulating barrier (Si ≤ 1.8 Å). Variation of the dynamic resistance and tunneling resistance with Si doping and applied bias in these MTJs indicate a transition from the Si-doped regime to Si cluster formation above a δ-layer thickness of about 1.2 Å, close to 1 monolayer coverage. The measurements show anomalously strong enhancements of the low frequency noise for Si thickness above 1.2 Å, mainly due to the appearance of random telegraph noise. A simple model, which considers suppression of Coulomb blockade in the array of Si dots, opening two-step tunnel channels, qualitatively explains the variation of both conductivity and noise with Si content.

1 Introduction Tunnelling phenomena in magnetic tunnel junctions have been attracting important attention for the last decade [1, 2]. The main efforts have concentrated on the increase of tunnelling magnetoresistance values, searching for new types of insulating barriers [3, 4]. Another research direction has emerged recently which is related to tunnelling in complex (hybrid) junctions. Manipulation of the barrier by doping with magnetic or nonmagnetic impurities or nonmagnetic, magnetic or superconducting dots [5–7], could add a new degree of freedom to spin polarized tunnelling and strongly enhance the versatility of spintronic devices based on this effect. Our work presents an experimental study of electron transport and low frequency noise in Co(80 Å)/Al_2O_3(10 Å)Si(δ)/Al_2O_3(2 Å)/Py(100 Å) hybrid magnetic tunnel junctions. We observed a continuous transition between the weak (Si impurities) and strong (array of Si quantum dots) regimes. In order to discriminate the different conductance regimes, we study the temperature and bias dependence of both the conductivity and TMR as a function of Si doping.

2 Experimental details Details of sample preparation have been published previously [6, 9]. For the silicon doped samples, after deposition of the underlying Co electrode, a first tunnel barrier was formed by deposition and subsequent oxidation of 10 Å of Al. Subsequently, submonolayer amounts of Si (of width δ in the following) were deposited on the Al_2O_3 surface, followed by a second Al layer deposition (2 Å) and oxidation, and by 100 Å of permalloy. We call positive bias the application of the voltage on the top Py electrode.

Measurements were performed using a computer controlled system [8, 9], which allows to detect the dynamic resistance, the DC value of the current and the voltage, and the noise in the device under study. Biasing of the samples was done at a constant current, applied using a calibrated source. It also allows modulating the applied current. The amplified signal was recorded in an analog-digital converter. Measurement of the noise uses the same biasing technique and the same low noise amplifiers, placed on top of a cryostat. The pre-amplified signals are further amplified by additional low-noise amplifiers (Stanford Research

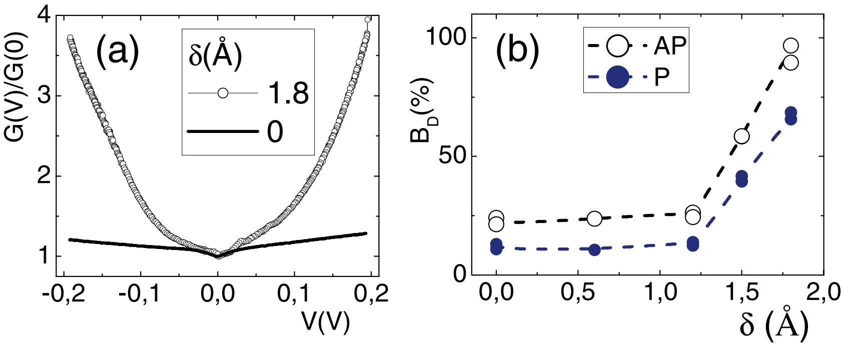

Figure 1 a) Dependence of the normalized conductance on bias voltage at low bias for undoped and a highly doped samples. b) Dependence of the parameter B_D, which characterizes the bias dependence of conductance, on silicon content (see text, Eq. (1)).

SR560). A spectrum analyzer SR780 calculates the cross-correlation spectrum of the voltage noise, containing thermal, shot and $1/f$ contributions. The obtained dynamic resistance allows to convert the voltage noise into the current noise.

3 Experimental data All measured MTJs show an enhancement of the resistance when the temperature is lowered down to 2 K, which rules out the presence of pinholes even for the highest silicon thickness. At room temperature the conductance is a parabolic function of the bias. However, below 100 K a peak of the form of the so-called zero bias anomaly appears in all MTJs at low bias, below 30 mV (see Fig. 1(a)).

These weak anomalies are similar both in the undoped and doped samples, possibly indicating a common origin. Besides, above 100 mV, the conductance shows strong variations with Si thickness. We have represented this behaviour in Fig. 1(b) by means of the parameter bias dependence (B_D):

$$B_D(\%) = 100\,\frac{R(0\text{ mV}) - R(100\text{ mV})}{R(100\text{ mV})}\,. \qquad (1)$$

It may be seen that it is weakly dependent on δ for low Si thickness, but increases sharply after a crossover region at $\delta = 1.2$ Å, close to the size of the atomic radius of Si.

Measurement of the variation with temperature of the low bias conductance has shown a linear dependence at temperatures below 20 K in all studied MTJs.

In Fig. 2(a) we show the zero bias tunnelling magnetoresistance (TMR) as a function of δ, at several selected temperatures. The influence of Si doping is strongest at room temperature, nearly suppressing TMR for $\delta = 1.8$ Å, while at low temperatures TMR only shows a slight decrease. In Fig. 2(b) we present an analysis of the bias dependence of TMR by plotting, as a function of δ, the bias voltage ($V_{\text{TMR/2}}$) needed to reduce TMR to one half of its zero bias value, at a temperature of 2 K. A low value of $V_{\text{TMR/2}}$ means a strong dependence on bias voltage. It is seen in the figure that this dependence increases strongly for $\delta > 1.2$ Å.

Electric noise in MTJs is composed of two components: “white” noise, which includes thermal and shot noises, and $1/f$ noise, reflecting resistance fluctuations. We have found that, at low temperatures, in all samples with $\delta \le 1.2$ Å the detected noise is “white” at frequencies above 1000 Hz, while the power spectrum is proportional to $1/f$ below this frequency. However, for high Si thickness we observe new features. For low bias (below 20 mV) the noise is similar to the other samples, but with increasing bias the low frequency noise increases very strongly reaching a maximum at a voltage of the order of 100 mV (Fig. 3(a)). This maximum has a higher value for positive bias. As may be seen in Fig. 3(b), the origin of this increase lies in the apparition of a Lorentzian line shape superimposed to the $1/f$ background. This Lorentzian is the signature of so-called random telegraph noise (RTN), as is shown in the time domain noise register of Fig. 3(c). In order to analyze the bias dependence of this noise of several samples, we have characterized its variance by the square root integral of noise over the finite frequency range of interest V_{RMS} (see Fig. 3(a)).

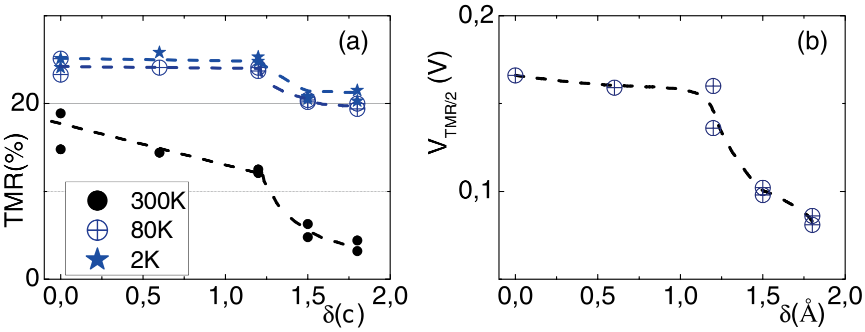

Figure 2 (online colour at: www.pss-a.com) a) Dependence of TMR on Si content at three selected temperatures. b) Bias dependence of TMR ($V_{\text{TMR/2}}$, see text) on Si content.

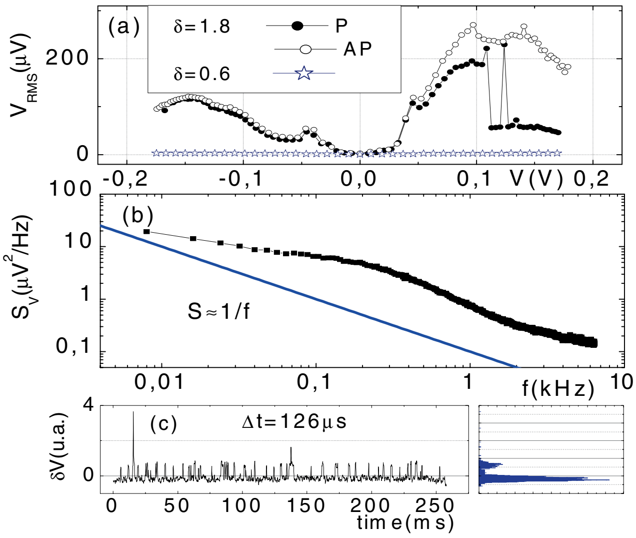

Figure 3 (online colour at: www.pss-a.com) a) Integrated noise (see text) as a function of bias voltage. Note the enhancement at high bias in the highly doped MTJ, and the asymmetry with respect to bias. b) Spectral power enhancement in a sample with $\delta = 1.8$ Å, due to the superposition of a Lorentzian line-shape to the $1/f$ background. c) Time domain register of RTN (left), giving rise to the Lorentzian, and histogram of number of counts at each voltage value.

4 Discussion and conclusions The main finding derived from these experimental results is that the behaviour of conductance and noise versus doping are closely related, and that there is a change in the physics of the MTJs when doping is increased over $\delta = 1.2$ Å, which corresponds roughly to one monolayer coverage. This may be qualitatively understood within the model of Zeller and Giaever [10] of two-steps tunnelling, controlled by Coulomb blockade. If the transition from having isolated Si impurities to Si islands in the barrier starts at a thickness around 1.2 Å, then the enhanced resistance B_D (Fig. 1(b)) could be attributed to the appearance of a new energy scale in electron transport, related to the finite capacitance of the silicon islands, practically absent for lower Si thickness. We have observed that the conductance for high δ tends to saturation, while for low δ and undoped samples the trend is maintained, as expected in normal MTJs with direct tunnelling. Within the Coulomb blockade model, the observed linear variation with temperature of the zero bias conductance at low temperatures may be attributed to the variation of the thermal population of electrons in the islands. For small δ two steps tunnelling is not possible due to Coulomb blockade, which is suppressed by the appearance of the Si islands, opening new conduction channels. This analysis is further supported by the bias dependence of TMR shown in Fig. 2(b).

We note here that there is also a crossover around $\delta = 1.2$ Å of the noise behaviour, which may be attributed to the changes in the Coulomb blockade phenomena. In undoped and with low Si content samples the low frequency noise is quite low, corresponding to normal MTJs with direct tunnelling. Besides, the measured “white” noise corresponds well to shot noise of uncorrelated tunnelling events. In MTJs with $\delta = 1.2$ Å there is some threshold voltage where two-step processes are allowed giving rise to the observed RTN. We believe that the maximum in noise versus bias (Fig. 3(a)) may indicate the transition from a regime of pure direct tunnelling to the regime including many current channels through the silicon islands, in a way that only in the intermediate zone some few fluctuators are activated, which give rise to RTN. The asymmetry of the maximum with respect to bias may be to an asymmetric situation in the environment of these fluctuators.

In conclusion, we have shown that conductance and low frequency noise measurements in doped MTJs are a useful tool to unveil different transport mechanisms in these systems.

Acknowledgements The work in Madrid has been supported by Spanish MEC (MAT2006-07196), Comunidad de Madrid (S-505/MAT0194) and ESF-AQDJJ programme. This work, as a part of the European Science Foundation EUROCORES Programme 05-FONE-FP-010-SPINTRA, was also supported by funds from the Spanish MEC and the EC Sixth Framework Programme, under Contract No. ERAS-CT-2003-980409. The work at MIT was supported by NSF and KIST-MIT project grants.

References

[1] J. S. Moodera, L. R. Kinder, T. M. Wong, and R. Meservey, Phys. Rev. Lett. **74**, 3273 (1995).
[2] T. Miyazaki and N. Tezuka, J. Magn. Magn. Mater. **139**, L231 (1995).
[3] S. S. P. Parkin, C. Kaiser, A. Panchula, P. M. Rice, B. Hughes, M. Samant, and S. H. Yang, Nature Mater. **3**, 862 (2004).
[4] S. Yuasa, T. Nagahama, A. Fukushima, Y. Suzuki, and K. Ando, Nature Mater. **3**, 868 (2004).
[5] J. Barnas and A. Fert, Phys. Rev. Lett. **80**, 1058 (1998).
[6] R. Jansen and J. S. Moodera, Phys. Rev. B **61**, 9047 (2000).
[7] S. Takahashi, H. Imamura, and S. Maekawa, Phys. Rev. Lett. **82**, 3911 (1999).
[8] R. Guerrero, F. G. Aliev, R. Villar, J. Hauch, M. Fraune, G. Güntherodt, K. Rott, H. Brückl, and G. Reiss, Appl. Phys. Lett. **87**, 042501 (2005).
[9] R. Guerrero, F. G. Aliev, Y. Tserkovnyak, T. S. Santos, and J. S. Moodera, Phys. Rev. Lett. **97**, 0266602 (2006).
[10] H. R. Zeller and I. Giaever, Phys. Rev. **181**, 7890 (1969).