



HAL
open science

Layer-resolved real space imaging of domain wall interactions in magnetic tunnel junctions

Jan Vogel, Salia Chérifi, Stefania Pizzini, Fabien Romanens, Julio Camarero, Frédéric Petroff, Stefan Heun, Andrea Locatelli

► **To cite this version:**

Jan Vogel, Salia Chérifi, Stefania Pizzini, Fabien Romanens, Julio Camarero, et al.. Layer-resolved real space imaging of domain wall interactions in magnetic tunnel junctions. 2007. hal-00133628v1

HAL Id: hal-00133628

<https://hal.science/hal-00133628v1>

Preprint submitted on 27 Feb 2007 (v1), last revised 8 Nov 2007 (v2)

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Layer-resolved real space imaging of domain wall interactions in magnetic tunnel junctions

J. VOGEL¹, S. CHERIFI¹, S. PIZZINI¹, F. ROMANENS¹, J. CAMARERO², F. PETROFF³, S. HEUN⁴ and A. LOCATELLI⁵

¹ *Institut Néel, CNRS & Université Joseph Fourier, BP166, 38042 Grenoble Cedex 9, France*

² *Dpto. Física de la Materia Condensada, Universidad Autónoma de Madrid, 28049 Madrid, Spain*

³ *Unité Mixte de Physique CNRS/Thales, Route Départementale 128, 91767 Palaiseau Cedex, France and Université Paris-Sud XI, 91405 Orsay Cedex, France*

⁴ *Laboratorio Nazionale TASC, S.S. 14, km 163.5 in Area Science Park, 34012 Basovizza, Trieste, Italy*

⁵ *Sincrotrone Trieste S.C.p.A., S.S. 14, km 163.5 in Area Science Park, 34012 Basovizza, Trieste, Italy*

PACS 75.60.Ch – Domain walls and domain structure

PACS 75.70.Kw – Magnetisation reversal mechanisms

PACS 07.85.Tt – X-ray microscopes

Abstract. - We have performed a layer-resolved, microscopic study of interactions between domain walls in two magnetic layers separated by a non-magnetic one, using high-resolution x-ray photoemission electron microscopy. Domain walls in the hard magnetic Co layer of a Co/Al₂O₃/FeNi trilayer with in-plane uniaxial anisotropy strongly modify the local magnetisation direction in the soft magnetic FeNi layer. Co domain walls parallel to the easy magnetisation axis induce ‘quasi-walls’ in an initially saturated FeNi layer. Charged Co domain walls that are tilted with respect to the easy magnetisation axis favour a local antiparallel alignment of the magnetisation directions in the two magnetic layers.

Introduction. – Magnetostatic interactions strongly influence both quasi-static and dynamic magnetic properties of spintronic devices such as magnetic tunnel junctions and spin valves. These devices make use of giant magnetoresistance (GMR), the difference in resistance for parallel and antiparallel alignment of the magnetisation directions in two magnetic layers separated by a non-magnetic one. This effect was first observed in Fe/Cr multilayers [1, 2]. The anti-ferromagnetic coupling between adjacent Fe layers in these multilayers allows an antiparallel alignment to be obtained in zero field, while a strong applied field leads to a parallel alignment. In the case of two magnetic layers of different coercivity, separated by a thin Cu layer, parallel and antiparallel configurations can be simply obtained by tuning the applied magnetic field [3]. In this case, magnetic interlayer coupling through the non-magnetic spacer is not necessary or even undesirable. In many cases, however, magnetic coupling is present in any case. This coupling can be due, for instance, to exchange or RKKY interactions (for thin metallic spacer layers) [4], or to dipolar interactions like the roughness induced Néel or orange-peel coupling [5]. Very strong magnetostatic ef-

fects can also be induced in the presence of domain walls (DWs) in one or both of the magnetic layers. Microscopic evidence of the influence of domain wall stray fields in one layer on the static domain configuration of another layer has been obtained by different groups [6–10]. In dynamic measurements, Thomas *et al.* [11] observed that repeated switching of the soft magnetic layer of a soft magnetic/nonmagnetic/hard magnetic trilayer can demagnetise the hard magnetic layer. This was attributed to stray fields of domain walls sweeping back and forth during the switching of the soft layer. We have recently shown [12] that in nanosecond magnetisation switching, domain walls in the hard magnetic Co layer in Fe₂₀Ni₈₀/Al₂O₃/Co trilayers can trigger nucleation in the soft FeNi layer and thereby increase the local switching speed. These observations were made taking advantage of the element selectivity, spatial and temporal resolution of X-ray Photoemission Electron Microscopy combined with x-ray magnetic circular dichroism (XMCD-PEEM) [13–16]. In this paper, we show results on the interaction between domain walls in these FeNi/Al₂O₃/Co trilayers in static conditions using high spatial resolution. These measurements nicely

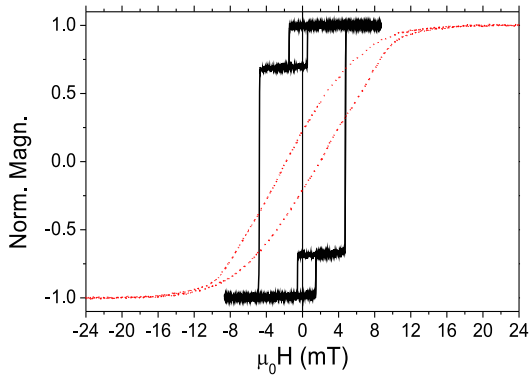


Fig. 1: Quasi-static hysteresis loops of the magnetic tunnel junction-like trilayer obtained by longitudinal Kerr effect. Loops obtained with the field applied along the easy (continuous line) and hard (dotted line) magnetisation axes are shown, as well as minor loops for the FeNi layer taken along the easy axis.

reveal the anti-parallel alignment between the magnetisation directions in the center of the Co domain wall and in the FeNi domain wall or quasi-wall just above. They also show that charged walls, which are tilted with respect to the magnetisation axis in the films, locally induce an antiparallel coupling between the two magnetic layers.

Experimental details. – The sample had the composition Si(111)/SiO₂/CoO(3nm)/Co(7nm)/Al₂O₃(2.6nm)/Fe₂₀Ni₈₀(4nm). It was covered with 3 nm of Al to protect the layers from oxidation. The Si(111) substrate was miscut by 8° along the [112] direction and then heat-treated to obtain a step-bunched surface, with terraces having an average width of 20 nm separated by 4 nm high steps [17]. For sufficiently thin films, this substrate topography is transmitted to the deposited layers [18,19]. The presence of elongated terraces leads to a shape-induced uniaxial magnetic anisotropy with the easy magnetisation axis along the long axis of the terraces. The correlated roughness at the two FM/NM interfaces leads to a magnetostatic orange-peel coupling [5] between the two magnetic layers [18,20]. The quasi-static magnetisation hysteresis loops of the sample, obtained using the longitudinal magneto-optical Kerr effect, are shown in Fig. 1. The quasi-static magnetisation reversal of this sample takes place by nucleation of a small number of domains and a subsequent propagation of the domain walls [21]. The minor loops of the FeNi layer reveal a coupling strength of about 1 mT.

In order to obtain high spatial resolution (< 40nm), we made use of the SPELEEM instrument at the Nanospectroscopy beamline at the synchrotron ELETTRA (Trieste, Italy) [22,23]. In this microscope, the x-rays hit the sample surface at a grazing incidence of 16°. It is therefore particularly suited for the study of samples with in-plane magnetisation. Element-selective magnetic contrast was obtained using XMCD, with the x-ray energy tuned to

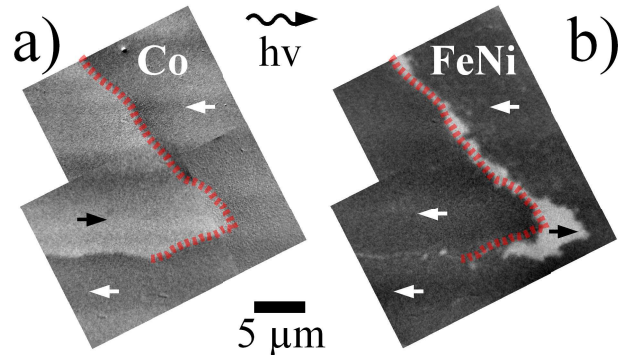


Fig. 2: Magnetic domain images of the Co (a) and FeNi (b) layers, after demagnetising the sample and consecutively re-saturating the FeNi layer. The directions of local magnetisation and of incoming photons are indicated with arrows. Part of the domain wall in the Co-layer is indicated in both images by a dotted red line.

the maximum of the Fe L₃ absorption edge (720 eV) for the FeNi layer and of the Co L₃-edge (793 eV) for the Co layer. The images, obtained at room temperature, represent the asymmetry (difference divided by sum) of two measurements taken with opposite photon helicity. This allows optimizing the magnetic contrast while minimizing topographic effects.

Results and discussion. – Before taking images, the sample was demagnetised outside the vacuum chamber, applying an AC magnetic field with decreasing amplitude along the easy magnetisation axis, in order to create a magnetic domain structure in both the FeNi and the Co layers. After demagnetising, a small constant field of about -3 mT was applied in order to saturate the FeNi layer without changing the domain structure in the Co layer. The sample was then introduced in the microscope, and several regions of interest were imaged. Figure 2 shows some typical magnetic domain images of the Co (a) and FeNi (b) layers. The images were obtained with the projection of the x-ray incidence direction on the sample surface parallel to the easy magnetisation axis. The contrast is due to the difference in absorption for domains with their magnetisation direction parallel and antiparallel to the incoming x-ray direction.

The image of the Co layer shows a domain structure typical for a magnetic layer with in-plane magnetic anisotropy. The domain wall at the bottom of the image is approximately parallel to the easy magnetisation axis while the other part is inclined by an angle of about 45°.

In the FeNi image, clear differences are observed between the regions above the two parts of the Co domain wall with different orientations. Above the parallel DW, a faint grey line is visible, indicating that the magnetisation is tilted away from the easy axis to form a ‘quasi-wall’ [12,24]. For the layer thicknesses used here, domain walls in both Co and FeNi layers are expected to be of Néel-type. The presence of the Néel wall in the Co-layer

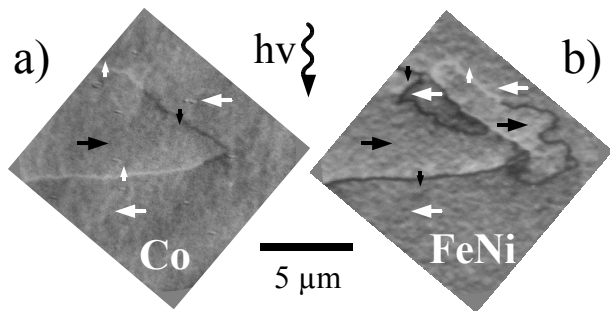


Fig. 3: Magnetic domain images of the Co (a) and FeNi (b) layers, taken with the incoming x-rays perpendicular to the easy magnetisation axis. The black and white regions correspond to domain walls, the grey regions to domains.

implies a local divergence of the magnetisation, leading to a stray field according to Maxwell's second equation. The direction of this stray field is opposite to the magnetisation direction in the center of the Co DW, perpendicular to the easy magnetisation axis.

In the vicinity of the inclined Co DW, much larger white domains are visible in the FeNi layer. The magnetisation directions in the Co layer around this DW are partly pointing towards each other, leading to a so-called 'head-on' DW. The stray field induced by this strongly charged DW is much stronger than for the parallel DW. In order to partly compensate the magnetic charges on the Co DW, an oppositely charged domain wall is formed in the FeNi layer (a tail-to-tail domain wall). The Co DW stray field therefore locally leads to an *antiparallel* coupling between the two magnetic layers through the alumina spacer, as is clearly seen in Fig. 2. This DW induced antiparallel coupling apparently is much stronger than the orange-peel coupling that favors parallel alignment.

In order to allow a better observation of the domain walls, we rotated the sample by 90° . This azimuthal rotation was performed outside the microscope, since an in-situ rotation was not possible. The images in Fig. 3 show domain patterns similar to the ones of Fig. 2, taken with the x-rays coming in along the hard magnetisation axis. In this case, the observed black and white regions correspond to the domain walls or quasi-walls, while the domains show intermediate grey contrast. In the left (Co) image, a zigzag domain wall is again observed, and the magnetisation direction at the center of the DW is indicated by the arrows. The likely magnetisation direction inside the domains is also given. Two Bloch lines (vortices), characterised by a reversal of the direction of magnetisation at the center of the DW, can be clearly observed.

Figure 3 (b) shows that domain walls or quasi-walls are present in the FeNi layer at exactly the same positions as in the Co layer. However, the contrast and thus the magnetisation direction at the center of the wall is opposite to the one in the Co layer. This is clear for the parallel wall, while it is more difficult to see in the tilted wall due to the

presence of additional domains and domain walls induced by the Co domain wall charges. This opposite alignment between the magnetisation directions at the center of the walls is expected from theory and from simulations [12].

Outside the domain wall region, contrast modulations are visible. These modulations are not due to noise, since they are reproducible between different series of images taken at the same position. This indicates that the local magnetisation direction can deviate from the global easy magnetisation axis. This is a reminder of the so-called 'ripple' structure often observed for uniaxial polycrystalline thin films when a magnetic field is applied perpendicular to the easy magnetisation axis. The phenomenon can be associated to the crystalline anisotropy of individual grains [25]. In our case, it is probably associated to a modulation of the long axis of the substrate terraces with respect to the easy [110] axis. The long axis of each terrace determines the local shape anisotropy, showing a distribution around the average, macroscopic easy magnetisation axis.

In Fig. 4, a different domain structure in the same sample is shown. In this case, the local magnetisation directions in the FeNi and Co layers are aligned with each other except in the regions close to the domain walls. Several Bloch lines, where the magnetisation direction at the center of the DW reverses, are clearly visible in the Co domain wall. The corresponding magnetisation direction at the center of the FeNi DW also changes sign due to the reversed direction of the Co DW stray field. Additional stray field components are generated around the Bloch line by its center (which presents a magnetisation direction perpendicular to the plane of the film [26]) and by the change of magnetisation direction along the DW, leading to a more complex magnetisation configuration in the FeNi film.

At the extremities of the ellipse-shaped Co domain, the inclined, charged domain walls induce small domains in the FeNi layer at both sides of the Co DW. As mentioned above, the magnetic charges in the Co layer can be partly compensated by creating charges of opposite sign in the FeNi layer. This leads to a strong anti-parallel coupling between Co and FeNi layers close to the charged Co domain walls. This influence of the domain wall charges is felt up to lateral distances of several micrometers from the domain wall center.

At several positions, a grey/black/white/grey contrast can be seen around domain walls in the FeNi layer. This is what is expected for a 360° domain wall, where the magnetisation vector makes a complete 360° turn going from one side of the domain wall to the other. However, also other configurations can give rise to this contrast. As an example consider the region in the circle of the FeNi image of Fig. 4. On the left, a black/white contrast is present. Going to the right, the black and white parts split. The white part is not associated to a DW in the Co layer, indicating that it has to be a normal 180° Néel wall. The black part separates two domains with the same magneti-

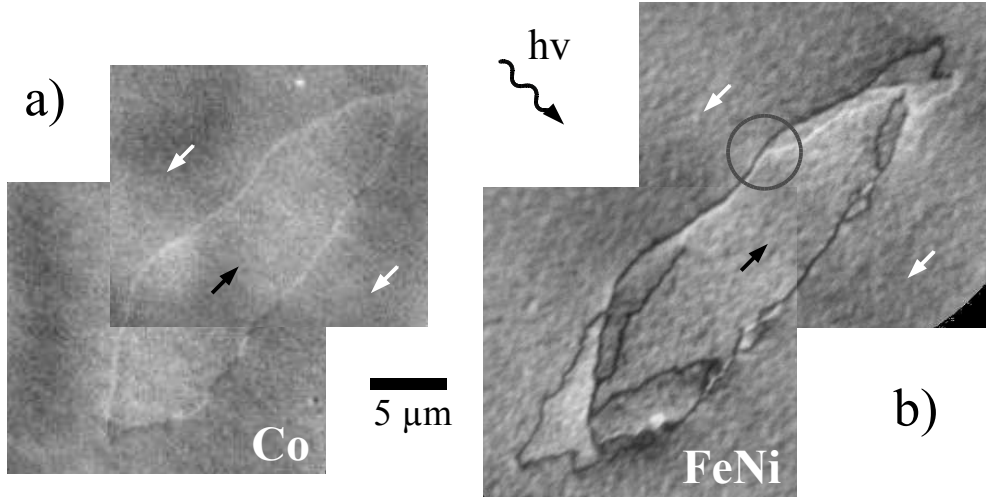


Fig. 4: Magnetic domain images of the Co (a) and FeNi (b) layers. The images were taken with the incoming x-ray perpendicular to the easy magnetisation axis, leading to a contrast induced by the domain walls only. The circle indicates a position where a 180° domain wall and a quasi-wall join.

sation direction and is therefore a ‘quasi-wall’, induced by the stray field of the Co domain wall. This means that, crossing the black/white region from right to left, the magnetisation vector turns over an angle of about 270° , before turning back -90° to end up at an angle of 180° with respect to the initial magnetisation direction. The contrast is thus induced by the combination of a Néel wall and a ‘quasi-wall’ with the same chirality.

These images can be used to obtain an estimate of the domain wall width in both layers. The definition we use for determining the domain wall width is based on the total wall flux and is given by $W_F = \int_{-\infty}^{\infty} \cos \varphi(x) dx$ [24], where $\varphi(x)$ is the angle between the local magnetisation direction and the hard magnetisation axis. This definition is the most convenient in our case, since the XMCD-intensity in the images of Fig. 3 is proportional to the projection of the local magnetisation direction on the x-ray incidence direction and thus to $\cos \varphi$. The wall width can be obtained by taking an image profile along a direction perpendicular to the DW. Using the highest resolution images (field of view $10 \mu m$), we find widths of 130 ± 20 nm for the Co domain walls and 170 ± 15 nm for the FeNi domain walls. However, the domain wall widths seem to be quite irregular, probably due to the specific, irregular topography of terraces and steps that can locally lead to confinement or largening of the domain walls [18]. The DW width of Co is smaller than for FeNi, as expected from the larger magnetic anisotropy of the Co layer. The influence of the Co DW stray field on the FeNi layer is therefore larger than the reciprocal effect, although it is visible in some images [27].

Time-resolved XMCD-PEEM measurements on this same sample already revealed the strong influence of the Co domain walls on the magnetisation reversal of the FeNi layer (Fig. 7 of Ref. [21]). In that case, a non-saturated

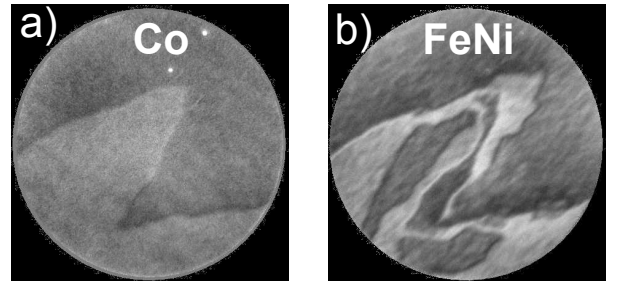


Fig. 5: Magnetic domain images of the Co (a) and FeNi (b) layers after application of several bipolar pulses with an amplitude of 5 mT. The images were taken with the x-rays coming in at an azimuthal angle of 10° with respect to the hard magnetisation axis.

region was observed in the FeNi layer just above the Co domain wall even for fields of 6 mT. This region seemed to be rather large (about $1 \mu m$), larger than we observe in these static images, even taking into account the difference in spatial resolution (about 50 nm here against 300 nm in Ref. [21]). In order to investigate the influence of repeated magnetic pulses on the domain walls, we recorded images of the Co and FeNi layers (Fig. 5) after application of some thousands of bipolar magnetic pulses of about 5 mT, using the same coil and pulsed current supply as in Refs. [21, 28].

The images were recorded with the x-rays coming in at an azimuthal angle of 10° with respect to the hard magnetisation axis. In this way it is possible to reveal the magnetisation direction in both the domains and the domain walls. The FeNi image clearly shows signs of domain accumulation around the Co domain wall over distances well above $1 \mu m$. Compression of these domains during the application of the field pulses might lead to 360° domain walls and be at the origin of the larger grey region

observed in the images of Ref. [21].

Conclusion. – We have performed layer-selective imaging of magnetic domains in FeNi/ Al₂O₃/Co trilayers with high spatial resolution. These images reveal the strong interaction between domain walls in the two magnetic layers. Co domain walls parallel to the easy magnetisation axis induce ‘quasi-walls’ in the FeNi layer, with the magnetisation at the centers of the two walls in opposite directions. For domain walls that are tilted with respect to the easy magnetisation axis magnetostatic interactions favor an anti-parallel alignment of the magnetisation directions in both magnetic layers over a distance up to several microns from the domain wall. Upon repetitive application of magnetic field pulses, these interactions can lead to an accumulation of domains and domain walls in the FeNi layer around the Co DW positions.

* * *

We acknowledge partial funding by the European Union under contract No. HPRN-CT-2000-00134 and by a Programme d’Actions Intégrées ‘Picasso’ (J.V. and J.C.), through Grant No. HF2003-0173. We thank A. Vaurès for her invaluable help in sample preparation.

REFERENCES

- [1] BAIBICH M., BROTO J., FERT A., NGUYEN VAN DAU F., PETROFF F., ETIENNE P., CREUZET G., FRIEDERICH A. and CHAZELAS J., *Phys. Rev. Lett.*, **61** (1988) 2472.
- [2] BINASCH G., GRÜNBERG P., SAURENBACH F. and ZINN W., *Phys. Rev. B*, **39** (1989) 4828.
- [3] DIENY B., SPERIOSU V., PARKIN S., GURNEY B., WILHOIT D. and MAURI D., *Phys. Rev. B*, **43** (1991) 1297.
- [4] BRUNO P. and CHAPPERT C., *Phys. Rev. B*, **46** (1992) 261.
- [5] NÉEL L., *C. R. Hebd. Seances Acad. Sci.*, **255** (1962) 1676.
- [6] FULLER H. and SULLIVAN D., *J. Appl. Phys.*, **33** (1962) 1063.
- [7] KUCH W., CHELARU L., FUKUMOTO K., PORRATI F., OFFI F., KOTSUGI M. and KIRSCHNER J., *Phys. Rev. B*, **67** (2003) 214403.
- [8] SCHÄFER R., URBAN R., ULLMANN D., MEYERHEIM H. L., HEINRICH B., SCHULTZ L. and KIRSCHNER J., *Phys. Rev. B*, **65** (2002) 14405.
- [9] CHRISTOPH V. and SCHÄFER R., *Phys. Rev. B*, **70** (2004) 214419.
- [10] WIEBEL S., JAMET J.-P., VERNIER N., MOUGIN A., FERRÉ J., BALTZ V., RODMACQ B. and DIENY B., *Appl. Phys. Lett.*, **86** (2005) 142502.
- [11] THOMAS L., SAMANT M. and PARKIN S., *Phys. Rev. Lett.*, **84** (2000) 001816.
- [12] VOGEL J., KUCH W., HERTEL R., CAMARERO J., FUKUMOTO K., ROMANENS F., PIZZINI S., BONFIM M., PETROFF F., FONTAINE A. and KIRSCHNER J., *Phys. Rev. B*, **72** (2005) 220402(R).
- [13] KUCH W., *Phys. Scr.*, **T109** (2004) 89.
- [14] VOGEL J., KUCH W., BONFIM M., CAMARERO J., PENNEC Y., OFFI F., FUKUMOTO K., KIRSCHNER J., FONTAINE A. and PIZZINI S., *Appl. Phys. Lett.*, **82** (2003) 2299.
- [15] BONFIM M., GHIRINGHELLI G., MONTAIGNE F., PIZZINI S., BROOKES N.B., PETROFF F., VOGEL J., CAMARERO J. and FONTAINE A., *Phys. Rev. Lett.*, **86** (2001) 3646.
- [16] SCHNEIDER C. M., KRASYUK A., NEPIJKO S. A., OELSNER A. and SCHÖNHENSE G., *J. Magn. Magn. Mater.*, **304** (2006) 6.
- [17] SUSSIAU M., NGUYEN VAN DAU F., GALTIER P., ENCINAS A. and SCHUHL A., *J. Magn. Magn. Mater.*, **165** (1997) 1.
- [18] PENNEC Y., CAMARERO J., TOUSSAINT J. C., PIZZINI S., BONFIM M., PETROFF F., KUCH W., OFFI F., FUKUMOTO K., NGUYEN VAN DAU F. and VOGEL J., *Phys. Rev. B*, **69** (2004) 180402(R).
- [19] MONTAIGNE F., *Effet tunnel dépendant du spin : Des simples aux doubles jonctions*, PhD thesis, Université Paris VII - Denis Diderot 1999.
- [20] ENCINAS A., NGUYEN VAN DAU F., SCHUHL A., MONTAIGNE F., SUSSIAU M. and GALTIER P., *J. Magn. Magn. Mater.*, **98-99** (1999) 15.
- [21] ROMANENS F., VOGEL J., KUCH W., FUKUMOTO K., CAMARERO J., BONFIM M., PIZZINI S. and PETROFF F., *Phys. Rev. B*, **74** (2006) 184419.
- [22] LOCATELLI A., BIANCO A., COCCO D., CHERIFI S., HEUN S., MARSI M., PASQUALETTO M. and BAUER E., *J. Phys. IV*, **104** (2003) 99.
- [23] LOCATELLI A., ABALLE L., MENTES T., KISKINOVA M. and BAUER E., *Surf. Interface Anal.*, **38** (2006) 1554.
- [24] HUBERT A. and SCHÄFER R., *Magnetic Domains : The Analysis of Magnetic Microstructures*. (Springer, Berlin - New York) 1998.
- [25] HARTE K. J., *J. Appl. Phys.*, **39** (1968) 1505.
- [26] WACHOWAK A., WIEBE J., BODE M., PIETZSCH O., MORGENSTERN M. and WIESENDANGER R., *Science*, **298** (2002) 577.
- [27] VOGEL J., ET AL., *unpublished*
- [28] VOGEL J., KUCH W., CAMARERO J., FUKUMOTO K., PENNEC Y., BONFIM M., PIZZINI S., PETROFF F., FONTAINE A. and KIRSCHNER J., *J. Appl. Phys.*, **95** (2004) 6533.