Available online at www.sciencedirect.com
SCIENCE DIRECT®
Journal of Magnetism and Magnetic Materials 283 (2004) 82–88
Journal of magnetism and magnetic materials
www.elsevier.com/locate/jmmm

Magnetic domains in a textured Co nanowire

W. Brückner[a], J. Thomas[a,*], R. Hertel[b], R. Schäfer[a], C.M. Schneider[a]

[a]*Leibniz-Institute for Solid State and Materials Research Dresden, P.O. Box 270116, D-01171 Dresden, Germany*
[b]*Max-Planck-Institute for Microstructure Physics, Weinberg 2, D-06120 Halle, Germany*

Received 16 February 2004
Available online 5 June 2004

Abstract

The magnetic domain structure in Co nanowires with dimensions $x \times y \times z = 70\,\mathrm{nm} \times 90\,\mathrm{nm} \times 2\,\mu\mathrm{m}$ was examined by Lorentz microscopy and micromagnetic simulations. A slab of two collinear Co nanowires separated by Cu were produced from a sputtered and annealed 90 nm Co/180 nm Cu/90 nm Co trilayer by transmission electron microscopy preparation methods. The easy axis of magnetisation in the Co wires with a hexagonal, *c*-axis-textured grain structure is parallel to the *y*-direction. The magnetic domains are periodic and have a size of about 80 nm. A partially open closure domain pattern with tilted magnetisation was found by numeric simulation.

PACS: 75.70.Kw; 75.75.+a; 68.37.Lp

Keywords: Domain structure; Nanowire; Lorentz microscopy; Micromagnetic simulation

1. Introduction

Cobalt single layers [1–3] and especially innovative magnetic nanostructures are of great interest for storage media and sensing devices. Examples of such nanostructures are magnetic Co/Cu multilayers exhibiting giant magnetoresistance (GMR) [4,5] and Co nanowires having unique magnetic properties and transport behaviour (domain wall magnetoresistance) [6–13].

For Co thin films, the magnetisation pattern depends on the film thickness. In polycrystalline films also the texture, depending on the deposition conditions and post-deposition annealing, plays a role, because it determines the size of the effective magnetic anisotropy [1,14–18].

Recently, the domain structure of Co nanowires and other nanostructures has been addressed by means of transmission electron holography [19], scanning electron microscopy with polarisation analysis [20], Lorentz microscopy with in-plane specimens [21], and magnetic force microscopy [22–25]. Usually, the Co nanowires were electrodeposited into an array of nanopores.

*Corresponding author. Tel.: +49-351-4659-250; fax: +49-351-4659-452
E-mail address: j.thomas@ifw-dresden.de (J. Thomas).

0304-8853/$ - see front matter
doi:10.1016/j.jmmm.2004.04.132

Prejbeanu et al. [25] used flat rectangular Co wires patterned from (1 0 0) epitaxial Co thin films. The investigations showed a strong influence of the geometry, the preparation conditions, and the magnetic history on the domain structure.

In general, the dimensionless Q-factor, i.e., the ratio between anisotropy and stray field energy, determines the domain type in finite size samples ($Q = K_u/2\pi M_s^2$, where K_u is the uniaxial magneto-crystalline anisotropy, M_s is the saturation magnetisation and $2\pi M_s^2$ is the stray field energy coefficient). On the one hand, if the anisotropy dominates ($Q > 1$), an easy-axis domain configuration will be formed throughout the sample, even if this will cause magnetic stray fields. On the other hand, if the stray field energy dominates ($Q1$), the magnetisation vector may deviate considerably from the anisotropy axis (at the expense of anisotropy energy), if this is necessary to avoid stray fields. Thus, a flux-closed domain configuration with closure domains will be formed.

Crystalline hexagonal cobalt has an uniaxial magneto-crystalline anisotropy $K_u = 4.0 \times 10^5\,\mathrm{J/m^3}$. This value yields a moderate quality factor $Q = 0.4$. According to Ref. [26, Chapter 3.7.4], a completely closed Landau model will become unfavourable in this case. A domain pattern is expected with partial flux closure at those surfaces which are perpendicular to the anisotropy axis. To be more precise, the magnetisation vector in the closure domains is not parallel to the surface, but tilted by a certain angle, thus causing magnetic surface charges. Additionally there is a partial opening between the closure domains, i.e., in a very small region the magnetisation meets the surface at 90°. For the wire geometry investigated in this paper, we expect such a partially open closure domain structure with tilted magnetisation.

The aim of the present article is the analysis of the magnetic domain structure in Co nanowires by means of Lorentz microscopy and micromagnetic simulations. We use a slab consisting of two collinear, highly textured Co nanowires separated by a Cu wire. This slab was produced from a sputtered and annealed Co/Cu/Co trilayer by means of transmission electron microscopy (TEM) preparation methods. We aim at a detailed description of the domain structure and the flux closure behaviour due to the high resolution of the magnetic imaging and the simulation. The investigations make contact to the studies of Prejbeanu et al. [25] on flat rectangular Co wires. These wires of various dimensions were processed by patterning epitaxial (1 0 0) Co thin films on (1 1 0) MgO substrates.

2. Lorentz microscopy

2.1. Samples and experimental

Trilayers are the basis for the preparation of the nanowires which are investigated in this article. In a previous paper [27], we studied the evolution of microstructure and the interdiffusion behaviour in 90 nm Co/180 nm Cu/90 nm Co trilayers during annealing. These trilayers were magnetron sputtered on 3-inch oxidised silicon wafers and subsequently annealed at 450 °C for 2 h under vacuum (8×10^{-6} mbar). During annealing, the grains of the as-deposited fine-grained microstructure grew in size to about the individual layer thickness. A change of the texture of the Co layers from a nearly random orientation to a pronounced c-axis texture occurs during this grain growth, as is also reported for Co single layers in Ref. [3]. More details about sample preparation, annealing, and microstructure of the as-sputtered and annealed trilayers are reported in Ref. [27]. Even though a small grain-boundary diffusion of Cu through the Co top layer to the surface as well as a distinct growth of Cu grains into the Co top layer occurs during annealing at 450°C, a well-structured Co/Cu/Co trilayer is preserved.

Using the TEM cross-section preparation technique, we cut two collinear nanowires from the trilayer by means of the focused ion beam technique (FIB). A sketch of the two nanowires which are separated by a Cu nanowire, is shown in Fig. 1. The magnetic easy axis (hexagonal c-axis, i.e., the average of the hexagonal c-axes in the highly textured microstructure) points perpendicular to the long axis of the Co nanowires.

The first step in our TEM investigations comprised conventional bright-field imaging. In this case, the specimen in the TEM is located

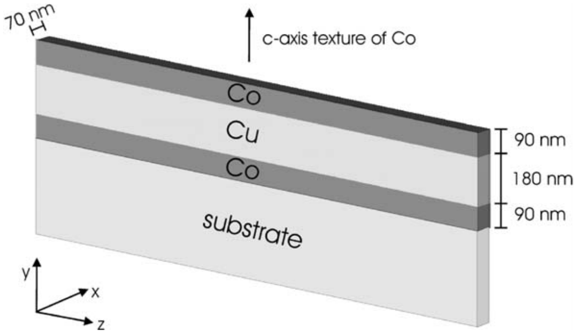

Fig. 1. Sketch of the two Co nanowires which are separated by a Cu wire. They were prepared from a Co/Cu/Co trilayer by a preparation technique for cross-section TEM specimens.

within the inhomogeneous magnetic field of the objective lens with a field strength of about 4 T. The sample magnetically saturates under these conditions. The field direction is perpendicular to the FIB cut, i.e., in the x-direction of Fig. 1. These circumstances define the magnetic history of the sample for Lorentz microscopy, i.e., the domains were observed in the remanent state after switching off the 4-T magnetic field.

To image domains by Lorentz microscopy, usually a special objective lens (Lorentz lens) is employed. If such a lens is not available (which is the case in our microscope), the objective lens has to be switched off (as commonly used in the low magnification mode), resulting in a drastic reduction of the resolution and a limitation of the magnification to about 2000. The Tecnai F30 instrument used for our investigations, however, is equipped with an imaging energy filter GIF200 which features an electron optics allowing a subsequent magnification of about 20 times. This results in a total magnification of up to 40 000 even without the objective lens.

2.2. Results and discussion

Lorentz microscopy exploits the deflection of electrons by the Lorentz force during their passage through domains with different directions of magnetisation. In the Fresnel mode, the domain boundaries are visible by bright and dark lines in the overfocused and underfocused image [28]. Using different focusing conditions, the series of pictures in Fig. 2 shows the magnetic contrast along the cross section of two nanowires separated by Cu. In both defocused images, a periodic domain structure can be seen. In the overfocused image in Fig. 2c the domain contrast is inverted, compared to the underfocused image in Fig. 2a, as is expected. The domain structure in the Co nanowire on the substrate side is highly periodic, whereas a more disturbed pattern is observed in the nanowire at the vacuum interface. Presumably, grains of cobalt oxide, which were formed during annealing as verified by analytical TEM [27], must be held responsible for the deterioration of the material which in turn causes domain deformation. Nevertheless, the domain structure formed far away from these defects is very similar to the domain structure in the nanowire next to the substrate.

The Lorentz image in Fig. 2 suggests a domain configuration as shown in Fig. 3. The domain structure considered corresponds roughly to the results of our numeric simulations (see below). The periodicity in the Lorentz image is twice the domain size, which amounts to 80–90 nm. The reduced length of the 180° domain walls in comparison to the wire dimension in y-direction as well as the course of the bright lines between the 180°-walls indicate the existence of flux closure domains. Details of the local rotation of the magnetisation cannot be extracted from these Lorentz images. The boundaries of the Co nanowires are emphasised by Fresnel fringes which are typical for defocused images.

3. Numeric simulations

3.1. Method

Numerical micromagnetic simulations were performed to investigate details of the magnetic microstructure in the cobalt nanowire. The equilibrium configuration of the magnetisation was calculated by minimising the total energy with respect to the discretised magnetisation field. Usually, the most important contributions to the

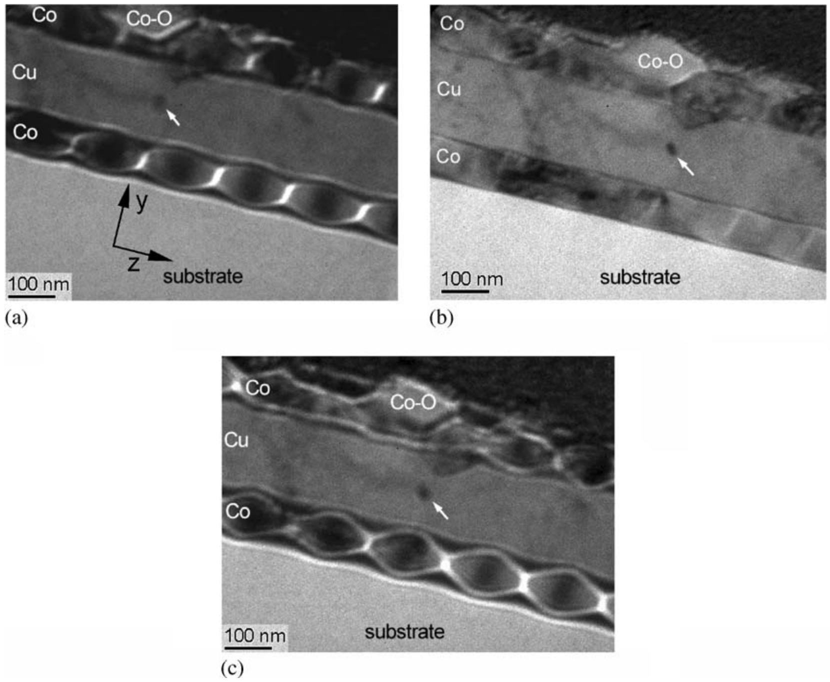

Fig. 2. Lorentz microscopy of magnetic domain walls in two Co nanowires separated by Cu, (a) in underfocus, (b) in focus, and (c) in overfocus. The arrows mark the same sample position.

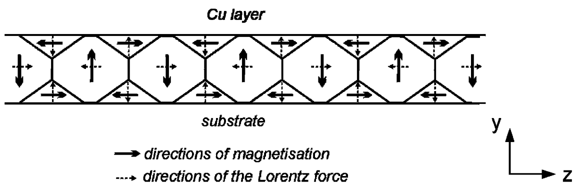

Fig. 3. Sketch of the domain structure and the directions of magnetisation with the resulting Lorentz forces for the beam electrons within the TEM as an explanation of the observed contrasts. Tilting in the closure domains, as resulted from the numerical simulations, is not considered.

energy of a ferromagnet at zero field are exchange, anisotropy, and stray field energy [29]. Calculating these energy terms involves an integration over the particle's volume. Numerically, the integration is replaced by a sum of integrals over the finite elements into which the sample is divided. We use tetrahedral finite elements, and the magnetisation is discretised at each corner point *i,* where its direction is defined by spherical coordinates φ_i and θ_i. These are the variables of the minimisation problem. A linear interpolation scheme is used within each element. The long-range interaction of the magnetostatic term is considered by solving the Poisson equation for the magnetic scalar potential [29]. Numerically, this is achieved by combining the boundary element method with the finite element method [30]. Details on the micromagnetic algorithm are described elsewhere [31].

The size of the sample considered in our simulations was $70\,\mathrm{nm} \times 90\,\mathrm{nm} \times 2\,\mu\mathrm{m}$, with the edges along the *x*-, *y*-, and *z*-axis, respectively. The number of nodal points in the finite element simulation was $10 \times 12 \times 250$. This discretisation is sufficient to find the coarse distribution of the magnetisation in this long nanowire. Nevertheless, for resolving the 180° domain walls and the closure behaviour, we additionally considered a short nanowire of dimension $70\,\mathrm{nm} \times 90\,\mathrm{nm} \times 2\,\mu\mathrm{m}$ with $21 \times 26 \times 63$ nodal points. To reflect the properties of Co, the saturation polarisation $J_s = 1.77\,\mathrm{T}$, the magneto-crystalline anisotropy constant $K_u = 4.0 \times 10^5\,\mathrm{J/m^3}$, and the exchange stiffness constant $A = 1.55 \times 10^{-11}\,\mathrm{J/m}$ for bulk Co were assumed. The easy axis was set parallel to the y-axis.

3.2. Results and discussion

The regular domain pattern with a characteristic periodicity which results from the simulation, is shown in Fig. 4 for the long wire dimension. The starting condition of the simulation was homogeneous (saturation) in the x-direction. This condition corresponds to the magnetic history of the sample in the Lorentz microscopy experiment (see above). Other starting conditions resulted in more irregular structures, also having higher energies (metastable domain structures). Thus, we consider the magnetic domain structure in Fig. 4 as the ground state configuration in a magnetic zero field. As expected, the magnetisation tends to align parallel to the easy axis. However, a homogeneous arrangement of the magnetisation would lead to strong demagnetising fields and thus to a high stray field energy. By means of periodic changes of the orientation of the magnetisation along the $\pm y$-direction the stray field energy is reduced at the expense of exchange energy. Further reduction of the stray field energy is obtained by the formation of closure domains (at the expense of anisotropy energy) which connect the flux between adjacent basic domains and appear as regions where the magnetisation direction alternates along $\pm z$. The spatial periodicity of the structure is an intrinsic property which results from an energetic balance of all energy terms [32], and is not connected with finite size effects along the z-direction. As a result of the simulations, we find a domain size of about 77 nm width, which is in fair agreement with the experimental findings.

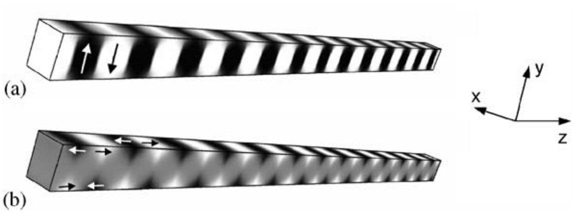

Fig. 4. Micromagnetic simulation of the long nanowire (70 nm × 90 nm × 2 μm). (a) The major domains along the easy axis change their direction periodically by 180°. (b) The wedge-shaped closure domains along the $\pm z$-direction partially close the flux connected with the domains along the easy axis. The grey scaling in (a) and (b) represents the value of the magnetisation components m_y and m_z, respectively.

A periodic domain structure was also obtained for the numeric simulation of the short nanowire (Fig. 5). Again, the basic domains are separated by 180° Bloch walls. On the $x-z$ surfaces, the magnetisation meets the surface in small regions at an angle of 90°. The closure behaviour can

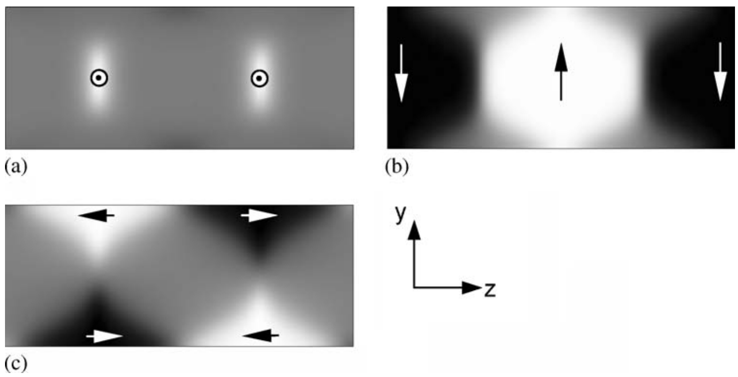

Fig. 5. Result of the numeric simulation for the short nanowire (70 nm × 90 nm × 2 μm) in a $y-z$ cross-section in a grey scale. (a), (b), and (c) give the x, y, and z component of the magnetisation in the middle of the nanowire, respectively. In (c), there is a tilting of magnetisation into the z-direction.

in fact be characterised as tilted (i.e., there are magnetic components perpendicular to the surface) with partial openings (meaning that the magnetisation meets the surface at an angle of 90° between the tilted closure domains, as predicted by a simple domain model in Ref. [26, Chapter 3.7.4C and Fig. 3.121b] for a material with $Q = 0.4$. However, our simulations reveal a continuous rotation of the magnetisation rather than regular domains with well-defined boundaries as simplistically assumed in Ref. [26].

4. Discussion and conclusions

At first, we compare the result obtained for the domain size to the model of Landau and Lifshitz [33], which treats the case of a perfect flux closure. The width w of domains in a magnetic layer is predicted to be

$$w = 2\sqrt{2t\sqrt{A/K_u}}, \tag{1}$$

where t is the film thickness. With the parameters used in the numerical simulation, one obtains $w = 67$ nm. Interestingly, this width is close to the values found both experimentally and by numeric simulations, although we are clearly not observing a perfectly closed magnetisation configuration.

Our findings confirm results on more extended Co structures which were obtained by magnetic force microscopy [34]. In the quoted paper, the structures were produced from (0 0 1) epitaxial thin films and showed a stripe domain pattern. Such domains are actually characterised by an oscillating magnetisation [26, Chapter 3.7.2], but in a first approximation they can be seen as regular, perpendicular basic domains with complete or tilted flux closure domains at the surfaces (depending on the Q-factor). On Co (0 0 1) bulk single crystals, such tilted closure domain patterns (though with ultrasharp domain walls) were found recently by Ding et al. [35] using spin-polarised scanning tunneling microscopy. The open stripe structure which was found on Co wires by Prejbeanu et al. [25] at our wire dimensions is not observed in our nanowires. Possible reasons may be the substrate influence (magnetoelastic contributions due to biaxial strain), the influence of dipolar interactions between adjacent wires, and differences in the resolution and contrast mechanism of Lorentz and magnetic force microscopy.

In conclusion, we established a well-behaved periodic domain pattern with a domain size of about 80 nm in Co nanowires with dimensions $x \times y \times z = 70\,\text{nm} \times 90\,\text{nm} \times 2\,\mu\text{m}$ and with c-axis texture along the y-axis. The magnetisation alternates parallel and antiparallel to the y-direction. The magnetic flux is partially closed by continuous magnetisation rotation that can be approximately described by a tilted closure domain model. The experimental results of Lorentz microscopy and the results of micromagnetic simulations agree fairly well.

Note that the domain pattern will also depend on the third dimension (the x-axis in our case). If the nanowire is additionally elongated along the x-axis, an extended layer would be obtained. The partial closure domains will then transform into dense stripe domains with a magnetisation component also in the x-direction (see Ref. [26, Chapter 3.7.2B]). Thus, we expect a dense stripe domain pattern for an extended Co/Cu/Co film configuration. The fine periodicity of the domain pattern explains the fact that we were not able to resolve the domains on such an extended film by Kerr microscopy with a lateral resolution of just about 300 nm. Our results confirm the interpretation of magnetostriction measurements in Co thin films which can only be explained by the occurrence of a considerable out-of-plane component of the magnetisation [3].

Acknowledgements

The authors are indebted to B. Arnold and D. Lohse for the electron microscopic preparation.

References

[1] A. Lisfi, J.C. Lodder, Phys. Rev. B 63 (2001) 174441.
[2] T. Kimura, F. Wakaya, J. Yanagisawa, Y. Yuba, K. Gamo, Jpn. J. Appl. Phys. 38 (1999) 4737.
[3] W. Brückner, M. Hecker, J. Thomas, D. Tietjen, C.M. Schneider, Mat. Res. Soc. Symp. Proc. 673 (2001) T3.3.

[4] K. Rätzke, M.J. Hall, D.B. Jardine, W.C. Shih, R.E. Somekh, A.L. Greer, J. Magn. Magn. Mater. 204 (1999) 61.
[5] M. Bobeth, M. Hecker, W. Pompe, C.M. Schneider, J. Thomas, A. Ullrich, K. Wetzig, Z. Metallkd. 92 (2001) 810.
[6] K. Ounadjela, R. Ferré, L. Louail, J.M. George, J.L. Maurice, L. Piraux, S. Dubois, J. Appl. Phys. 81 (1997) 5455.
[7] R. Ferré, K. Ounadjela, J.M. George, L. Piraux, S. Dubois, Phys. Rev. B 56 (1997) 14006.
[8] J.-E. Wegrowe, D. Kelly, A. Franck, S.E. Gilbert, J.-Ph. Ansermet, Phys. Rev. Lett. 82 (1999) 3681.
[9] R.M. Metzger, V.V. Konovalov, M. Sun, T. Xu, G. Zangari, B. Xu, M. Benakli, W.D. Doule, IEEE Trans. Magn. 36 (2000) 30.
[10] K. Matsuyama, S. Komatsu, Y. Nozaki, J. Appl. Phys. 87 (2000) 4724.
[11] J.-E. Wegrowe, A. Comment, Y. Jaccard, J.-Ph. Ansermet, N.M. Dempsey, J.-P. Nozières, Phys. Rev. B 61 (2000) 12216.
[12] U. Ebels, A. Radulescu, Y. Henry, L. Piraux, K. Ounadjela, Phys. Rev. Lett. 84 (2000) 983.
[13] P.M. Paulus, F. Luis, M. Kröll, G. Schmid, L.J. de Jongh, J. Magn. Magn. Mater. 224 (2001) 180.
[14] K.M. Krishnan, T. Takeuchi, D.M. Donnet, K. Tanahashi, J. Appl. Phys. 75 (1994) 7579.
[15] T. Duden, E. Bauer, Phys. Rev. Lett. 77 (1996) 2308.
[16] M. Löhndorf, A. Wadas, R. Wiesendanger, Appl. Phys. A 65 (1997) 511.
[17] A.C.C. Yu, A. Petford-Long, T. Miyazaki, Jpn. J. Appl. Phys. 40 (2001) 4891.
[18] A. Kazedi Mukenga Bantu, J. Rivas, G. Zaragoza, M.A. López-Quintela, M.C. Blanco, J. Non-Cryst. Solids 287 (2001) 5.
[19] C. Beeli, B. Doudin, J.-Ph. Ansermet, P.A. Stadelmann, Ultramicroscopy 67 (1997) 143.
[20] J.A. Borchers, J.A. Dura, J. Unguris, D. Tulchinsky, M.H. Kelley, C.F. Majkrzak, S.Y. Hsu, R. Loloee, W.P. Pratt, Jr., J. Bass, Phys. Rev. Lett. 82 (1999) 2796.
[21] K.J. Kirk, J.N. Chapman, C.D.W. Wilkinson, J. Appl. Phys. 85 (1999) 5237.
[22] Y. Henry, K. Ounadjela, L. Piraux, S. Dubois, J.-M. George, J.-L. Duvail, Eur. Phys. J. B 20 (2001) 35.
[23] D.H. Qin, M. Lu, H.L. Li, Chem. Phys. Lett. 350 (2001) 51.
[24] J.M. Garcia, A. Asenjo, M. Vazquez, P. Aranda, E. Ruiz-Hitzky, IEEE Trans. Magn. 36 (2000) 2981.
[25] I.L. Prejbeanu, L.D. Buda, U. Ebels, M. Viret, C. Fermon, K. Ounadjela, IEEE Trans. Magn. 37 (2001) 2108.
[26] A. Hubert, R. Schäfer, Magnetic Domains, Springer, Berlin, 1998.
[27] W. Brückner, S. Baunack, J. Thomas, M. Hecker, C.M. Schneider, J. Appl. Phys. 91 (2002) 9696.
[28] A. Hubert, R. Schäfer, Magnetic Domains, Springer, Berlin, 1998 p. 297.
[29] W.F. Brown Jr., Magnetostatic Principles in Ferromagnetism, North-Holland, Amsterdam, 1962.
[30] D.R. Fredkin, T.R. Koehler, IEEE Trans. Magn. 26 (1990) 415.
[31] R. Hertel, J. Appl. Phys. 90 (2001) 5758.
[32] W. Rave, A. Hubert, J. Magn. Magn. Mater. 197 (1999) 325.
[33] L. Landau, E. Lifshitz, Physik. Z. Sowjetunion 8 (1935) 153.
[34] A.D. Kent, U. Rüdiger, J. Yu, L. Thomas, S.S.P. Parkin, J. Appl. Phys. 85 (1999) 5243.
[35] H.F. Ding, W. Wulfhekel, J. Kirschner, Europhys. Lett. 57 (2002) 100.