PhD thesis booklet

MAGNETIC PHASE AND DOMAIN EVOLUTION OF ANTIFERROMAGNETICALLY COUPLED MULTILAYERS

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Introduction

Nanotechnology is one of the research priorities of present-day industrial societies. Both basic and applied research benefits from the new materials, which can be engineered on the atomic scale. Due to the immense development of the experimental techniques in materials science, the production of structures of reduced dimensions is not a problem anymore. The growth and investigation of thin films, quantum dots etc. is an everyday scientific task.

The artifical nanostructures found their way to the research of magnetism, too. Magnetic thin films help in understanding the fundamental magnetic interactions in matter and the industrial applications are also immense. For example Magnetic RAMs are offering a new way for information storage and might be for computing in general. The perpendicular recording media is already available commercially and read heads based on giant magnetoresistance (GMR) are used in all in hard drives today. GMR was discovered in 1988 and already in 1997 the first GMR hard disk hit the market.

The physical background for the resistance change in GMR devices is the parallel realignment of antiferromagnetically (AF) coupled spins of consequtive ferromagnetic layers by the application of a magnetic field. The underlying effect, viz. the AF coupling of magnetic layers was discovered in 1986 by Grünberg *et al.* on a trilayer, which consisted of ferromagnetic Fe layers sandwiched by Cr spacers. Despite the fact that AF coupling was found in many multilayer (ML) systems, Fe/Cr MLs certainly belong to the most investigated ones. This is partly due to the still not fully understood coupling behaviour of this system.

Another aspect of the AF-coupled MLs is their domain structure. In contrast to ferromagnetic films and structures in a strongly AF-coupled ML, the stray field of the domains is in large compensated thus other forces may influence the appearance of the domains. This is also obvious from the comparison of the patch-like AF domains to the characteristic ripple domains of ferromagnetic thin films. Formation of patch domains is mainly governed by fluctuations of the AF coupling resulting in a lateral distribution of the saturation field. The seemingly small effect of external field believed to prohibit the manipulation of the AF domains. However, one may wish to control the domain size, a parameter profoundly influencing the noise of magnetoresistive devices.

Aims of the present work

In order to understand the magnetic behavior of thin films better we decided to

- find a `coherent' description of the strongly AF-coupled MLs in magnetic field, including the finite stacking effects and to
- describe the domain evolution of a Fe/Cr ML, mainly the phenomena of domain ripening, supersaturation and domain coarsening.

Applied methods

For the modeling of MLs with finite stacking a computer code was written. The MLs were characterized structurally and magnetically with common methods (x-ray scattering, VSM[§], SQUID) and due to the bilayer-thickness uncertainty, with applied nuclear methods (RBS, PIXE).

The thoroughly qualified sample was investigated in details by SMR and PNR techniques. The advantage of the latter two is that they give a coherent picture of the sample, thus the structural and magnetic information can be distinguished. For AF aligned MLs extra peaks appear in the position of so-called half order Bragg peaks due to the magnetic cell doubling. SMR and PNR are also capable of measuring plane-perpendicular and lateral (parallel to the surface of the ML) structure and correlations. For the latter, off-specular (or diffuse) scattering is used.

The sample under investigation was a strongly coupled Fe/Cr ML with fourfold in-plane anisotropy. The two perpenicular easy axes permits the investigation of the so-called bulk spin-flop (BSF) transition. The iron layers were made of ^{57}Fe, which is needed for the SMR measurements.

Theses

1. A computer code with conjugate gradient optimization was developed by the author [1]. The finite stacking effects were included in the program, with single-domain approximation. It was shown that the correction of the net magnetization of the ML is diminishing rapidly with increasing number n of layers and even much faster, than the naively expected $1/n$ factor. New phases due to the extra freedom of the end layers were shown to occur.
2. The author gave an upper theoretical limit on the critical field of the BSF transition [3]. This limit is analytical function of the ML parameters (magnetization, AF coupling, anisotropy, etc.). Finite stacking effects were included [4] in the calculations. For hard direction magnetization loops a phase resembling the surface spin flop was found by numerical

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[§] VSM: Vibrating Sample Magnetometry, SQUID: Superconducting Quantum Interference Device, RBS: Rutherford Backscattering Spectrometry, PIXE: Particle-Induced X-ray Emission, SMR: Synchrotron Mössbauer Reflectometry, PNR: Polarized Neutron Reflectometry simulations. The spin-state was found to depend on the magnetic history of the ML. In hard direction unsaturation the spins can partition to two orthogonal directions separated by a transition region of few spins in the middle of the ML stack (X-phase).

3. The author successfully fitted the magnetization curves of an AF coupled Fe/Cr ML with an extended bilinear-biquadratic model function. From RT and 20 K VSM measurements the BSF field was deduced. The small field of the BSF transition compared to the theoretical maximum of the local energy path minimization suggests, that the BSF transition is mainly governed by domain wall movement and not coherent spin rotation [4]. The hard direction MOKE measurements were analyzed by the author and the small jump in magnetization attributed to the appearance of the spin partition phase.
4. The time intergal SMR spectra measured at ESRF were evaluated in great detail. Contrary to `traditional' magnetization measurements, SMR and PNR can confirm directly the existence of the BSF transition. The author contributed in the determination of the BSF field. It was found to be between the narrow field range of 12–16 mT.
5. We developed a simple model of patch-domain formation on unsaturation based on the random fluctuations of the saturation filed and the minimization of the domain-wall length. Magnetic layers were divided to pixels and first-neighbor spin-flop rules set, Monte Carlo simulation was done by the author. The autocorrelation function of an AF-coupled trilayer, measured by Kerr microscopy was described by the model [5]. The model was developed further in order to describe domain ripening and coarsening [6,7].
6. The transformations of AF domains were investigated by SMR and PNR on an Fe/Cr ML. The author participated in the description of the measured sample history:
    a. In releasing the field from ~ 1.3 T (the supersaturating field, see c.) the domains, which are approximately (370 nm) wide after formation, ripen in the (0.2-0.1 T) region independently of the orientation of the fourfold in-plane anisotropy. In the ripening process the domains irreversibly grow approximately by an order of magnitude [8].
    b. Decreasing the field further to remanence, in the case of hard direction loop the domains may be parallel to all four easy directions (X-phase, spin partition), but no further ripening is associated with the partition.
    c. To get back the primary small domain state, the sample must be supersaturated in a field of at least 1.3 T. The supersaturation is even more pronounced at low temperature. In the case of 15 K we know from SMR measurements that the saturation field is 1,5 T , while the supersaturation field is at least 2,5 T (but smaller than 4 T). In remanence small domains were found (no ripening occurs).

d. The BSF transition is accompanied by domain coarsening. The domains flipped by 90° are in fact so large, that neither SMR nor PNR show diffuse magnetic scattering, thus only a lower size-limit of 30 μm can be given [2].

Conclusions

For AF-coupled MLs the finite stacking effects are important. The extended bilinear-biquadratic model makes it possible to predict the results of different kinds of magnetic measurements. The size of the patch-domains may depend on the external field and it is possible to enlarge the domains considerably, which could result in the suppression of GMR noise. This latter effect could have industrial application, too.

List of Publications

Papers directly connected to theses

[1] M. Major, L. Bottyán, L. Deák, D. L. Nagy; „On magnetic multilayers of finite stacking”. in E.A. Görlich, A. Pedziwiatr, editors, *Condensed Matter Studies by Nuclear Methods*, Proc. XXXIV. Zakopane School of Physics, Zakopane, pages 165–168. Jagellonian University, Cracow, (1999).

[2] D. L. Nagy, L. Bottyán, L. Deák, M. Major; „Synchrotron Mössbauer Reflectometry – Recent Applications in Multilayer Magnetism”. *Acta Physica Polonica A*, **100**, 669–678, (2001).

[3] D. L. Nagy, L. Bottyán, B. Croonenborghs, L. Deák, B. Degroote, J. Dekoster, H. J. Lauter, V. Lauter-Pasyuk, O. Leupold, M. Major, J. Meersschaut, O. Nikonov, A. Petrenko, R. Rüffer, H. Spiering, and E. Szilágyi. “Coarsening of antiferromagnetic domains in multilayers: The key role of magnetocrystalline anisotropy.” *Phys. Rev. Lett.*, **88**, 157202, (2002).

[4] L. Bottyán, L. Deák, J. Dekoster, E. Kunnen, G. Langouche, J. Meersschaut, M. Major, D. L. Nagy, H. D. Rüter, E. Szilágyi, and K. Temst. “Observation of the bulk spin-flop in an Fe/Cr superlattice”. *J. Magn. Magn. Mat.*, **240**, 514–516, (2002).

[5] M. Major, L. Bottyán, and D. L. Nagy. “Simulation of unsaturation domain formation in antiferromagnetic multilayers”. *Acta Physica Polonica A*, **101**, 301–305, (2002).

[6] M. Major, L. Bottyán, and D. L. Nagy. “Simulation of antiferromagnetic domain formation history in magnetic multilayers”. *Phys. Stat. Sol. (a)*, **189**, 995–999, (2002).

[7] M. Major, L. Bottyán, and D. L. Nagy. “Simulation of domain formation and domain coarsening in antiferromagnetic multilayers”. *J. Magn. Magn. Mat.*, **240**, 469–471, (2002).

[8] D. L. Nagy, L. Bottyán, L. Deák, B. Degroote, O. Leupold, M. Major, J. Meersschaut, R. Rüffer, E. Szilágyi, J. Swerts, K. Temst, A. Vantomme; „Specular and Off-Specular Synchrotron Mössbauer Reflectometry: Applications to Thin Film Magnetism”. *Phys. Stat. Sol. (a)*, **189**, 591–598, (2002).

Other publications on the topics of the paper

[A] D. L. Nagy, L. Bottyán, L. Deák, B. Degroote, J. Dekoster, O. Leupold, M. Major, J. Meersschaut, R. Rüffer, E. Szilágyi, A. Vantomme. „Off-specular synchrotron Mössbauer reflectometry: A novel tool for studying the domain structure in antiferromagnetic multilayers”. *Hyperfine Interactions*, **141-142**, 459–464, (2002).

[B] D. L. Nagy, L. Bottyán, L. Deák, B. Degroote, J. Dekoster, O. Leupold, M. Major, J. Meersschaut, R. Rüffer, E. Szilágyi, A. Vantomme; „Off-specular synchrotron Mössbauer reflectometry: A novel tool for studying the domain structure in antiferromagnetic multilayers”; *Hyperfine Interactions*, **141-142**, 459–464, (2002)

[C] L. Deák, L. Bottyán, M. Major, D. L. Nagy, H. Spiering, E. Szilágyi, F. Tanczikó; „Recent Developments in Synchrotron Mössbauer Reflectometry”. *Hyperfine Interactions*, **144**, 45–52, (2002)

[D] Nagy Dénes Lajos, Bottyán László, Deák László, Major Márton, Szilágyi Edit, Tanczikó Ferenc, „Domének keletkezése és átalakulásai antiferromágnesesen csatolt multirétegekben”, *Fizikai Szemle,* **LIV**, 368–372, (2004).