Ripening of Domains in Antiferromagnetically Coupled Multilayers: Experiment, Cellular Automaton Model and DWBA Calculation

D.L. Nagy[1], L. Bottyán[1], A.I. Chumakov[2], L. Deák[1], E. Harth[1], M. Major[1], R. Rüffer[2], E. Szilágyi[1], F. Tanczikó[1] and D. Visontai[1]

[1]KFKI Research Institute for Particle and Nuclear Physics, P.O.B. 49, H-1525 Budapest, Hungary
[2]European Synchrotron Radiation Facility, BP 220, F-38043 Grenoble, France

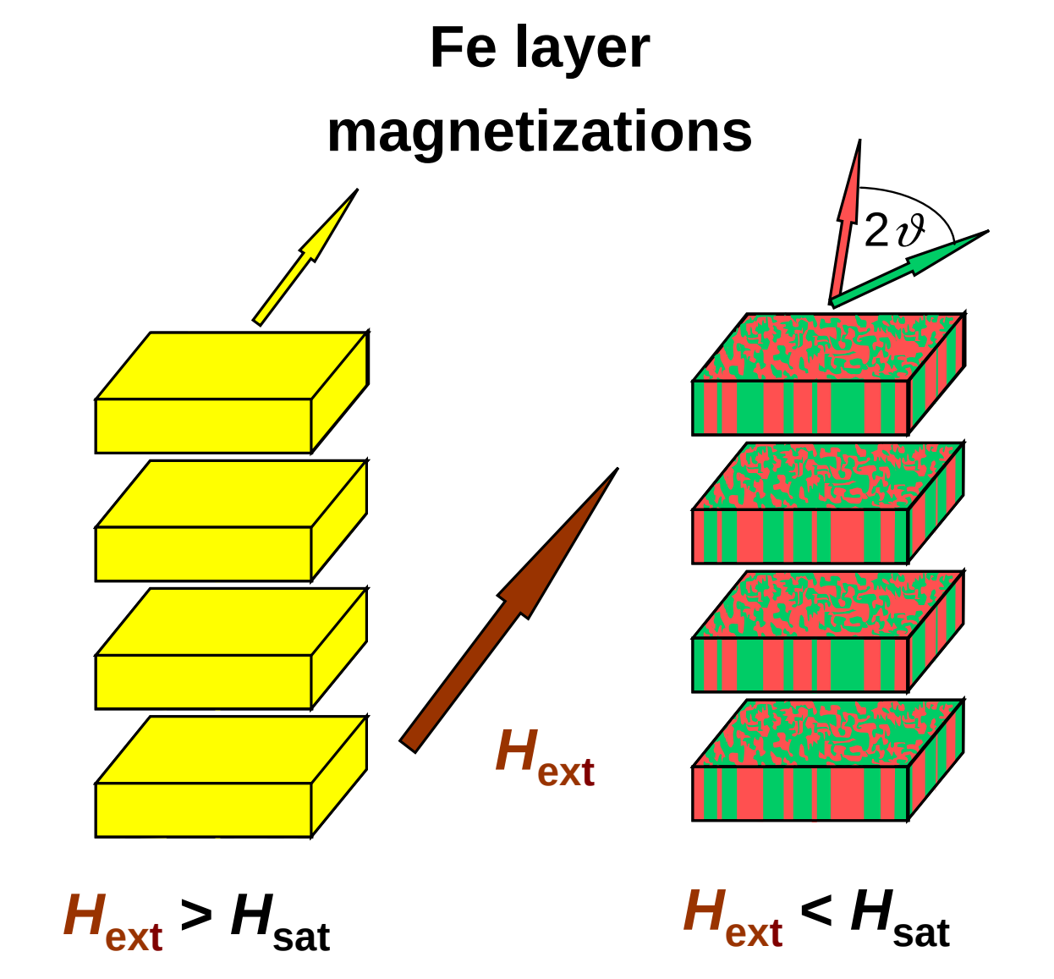
Introduction

Antiferromagnetically (AF) coupled metallic multilayers (ML) have received much attention in recent years due to their relevance in fundamental science and magnetic recording technology alike. The performance of magnetoresistive devices is strongly affected by the ML domain structure. Here we present studies of *domain ripening* in strongly AF-coupled epitaxial MLs by synchrotron Mössbauer reflectometry (SMR). The observed transformation will be described by a Monte Carlo simulation and the qualitative shape of the diffuse SMR scatters will be interpreted in terms of a distorted-wave Born approximation (DWBA) calculation.

Domain formation and domain ripening

According to SMR and polarised neutron reflectometry (PNR) experiments, in strongly AF-coupled multilayers, the domain size depends on the full history of magnetic field and temperature. Starting in magnetic saturation and then gradually decreasing the field, two kinds of AF patch domains differing only in the sense of rotation (SOR) of the magnetisation in their odd and even layers are spontaneously formed [1]. On further decreasing the field and, thereby, increasing the domain-wall (DW) angle, the size of the domains spontaneously and irreversibly increases in order to decrease the DW energy per unit area of the ML [2]. This phenomenon is the *domain ripening*.

Domain formation

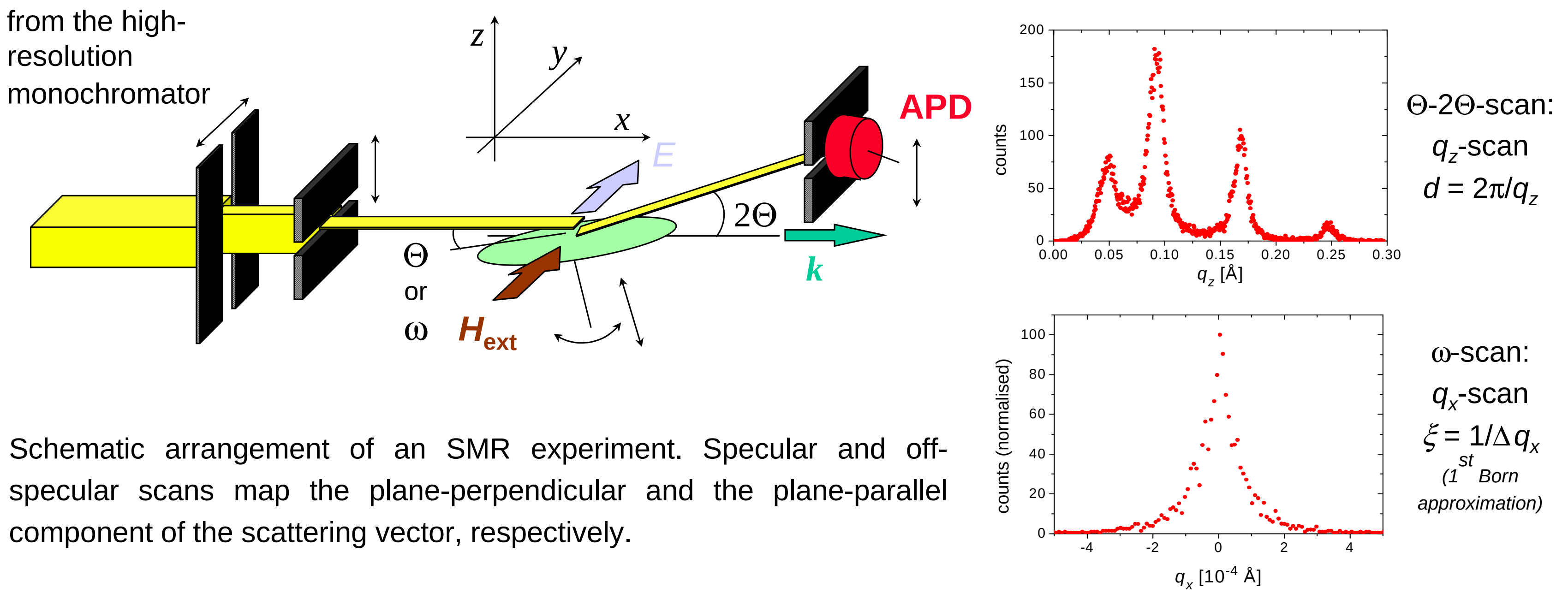


Formation of patch domains in a strongly AF-coupled Fe/Cr multilayer on leaving the saturation region. Red and green domains only differ in the sense of rotation of the magnetization. Yellow indicates saturation. The Cr spacer layers are not shown.

The pixel model

A micromagnetic simulation describing the details of the observed domain ripening transformations would involve about 10^{12} spins and is, therefore, not feasible. An alternative phenomenological model, the basic unit of which, the *pixel* consists of about 10^8 strongly correlated spins is presented here. Pixels are small, homogeneous regions of the ML with lateral dimensions larger or nearly equal to the domain-wall width and less than the domain size. It is assumed that the AF order is retained through the whole ML stack which, in an applied magnetic field H, is described in terms of a two-sublattice model of opening angle 2ϑ. As a further supposition, we assign a lateral distribution (e.g., of Gaussian type) to the layer-layer coupling and, consequently, to the saturation field $H_S(\mathbf{r})$. Pixels are defined on a rectangular lattice. The domain state of the ML is described by the pixel magnetisation pattern. Since the pixel is smaller than a domain, the absolute value of its ferromagnetic layer magnetisation is constant and equal to the bulk ferromagnetic saturation magnetisation M. For pure bilinear layer-layer coupling, the half opening angle of a pixel is $\vartheta = \arccos(H/H_S(\mathbf{r}))$. The autocorrelation function of the magnetisation of the odd (or even) layers related to the shape of diffuse scattering curves is calculated from the pixel pattern. The total magnetisation of the ML is the sum of the pixel magnetisations.

Synchrotron Mössbauer reflectometry (SMR)

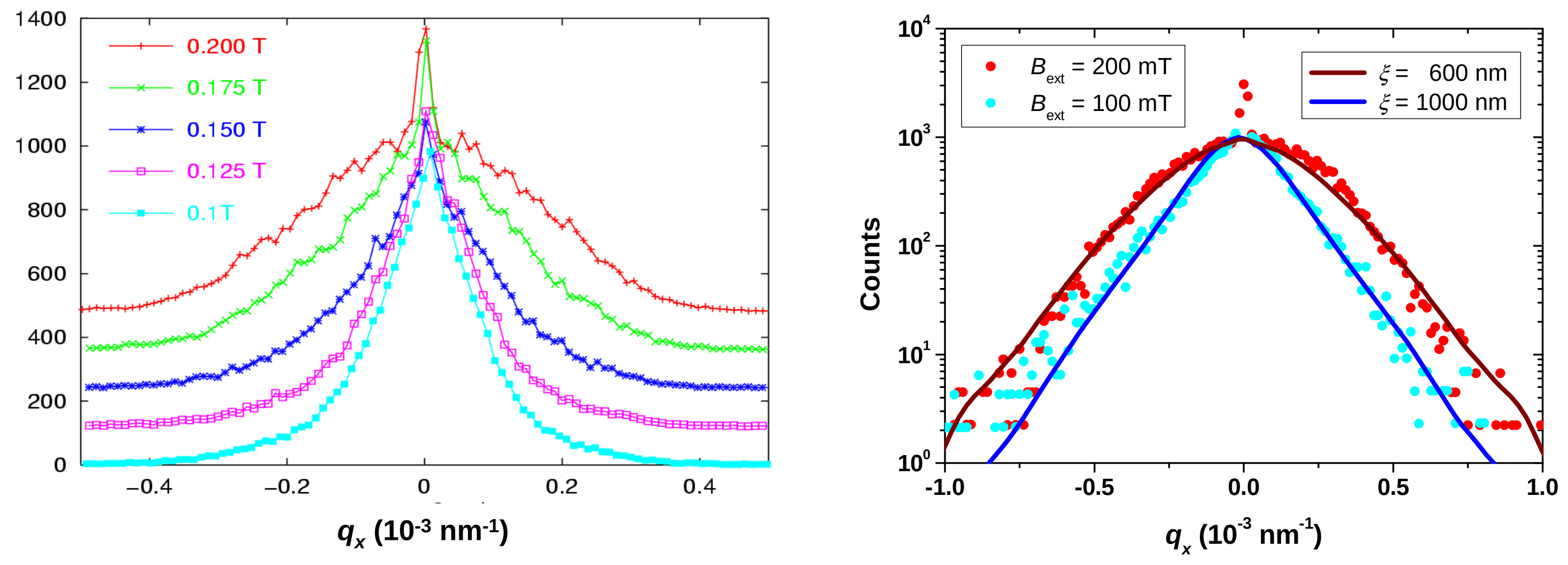


Schematic arrangement of an SMR experiment. Specular and off-specular scans map the plane-perpendicular and the plane-parallel component of the scattering vector, respectively.

Experiment

An epitaxial MgO(001)/[^{57}Fe(2.6 nm)/Cr(1.3 nm)]$_{20}$ ML was fabricated by MBE technique. Diffuse (i.e., off-specular) SMR experiments were performed at the nuclear resonance beamline ID18 of the European Synchrotron Radiation Facility, Grenoble. The ML was placed in a liquid helium cryostat equipped with a superconducting solenoid and a variable temperature inset. At 295 K, domain ripening was observed between 200 and 100 mT in decreasing external magnetic field.

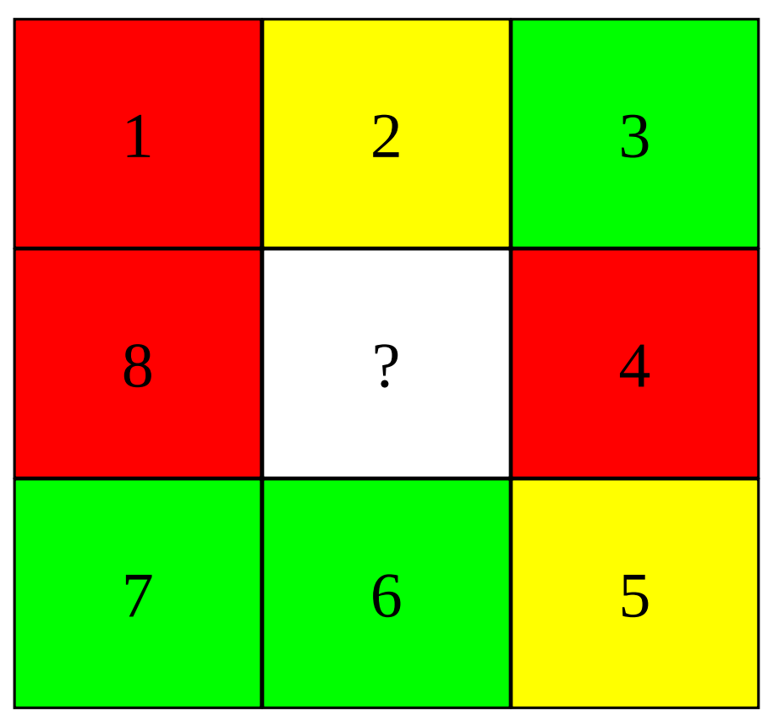
Domain ripening during demagnetisation



Ripening is a spontaneous and irreversible growth of the domain size (i.e., of the magnetization correlation length ξ) in an external magnetic field decreasing from the saturation region. The driving force of ripening is the domain-wall energy density, which is increasing due to the increase of the domain-wall angle. Ripening is connected with domain-wall movement and is, therefore, limited by coercivity.

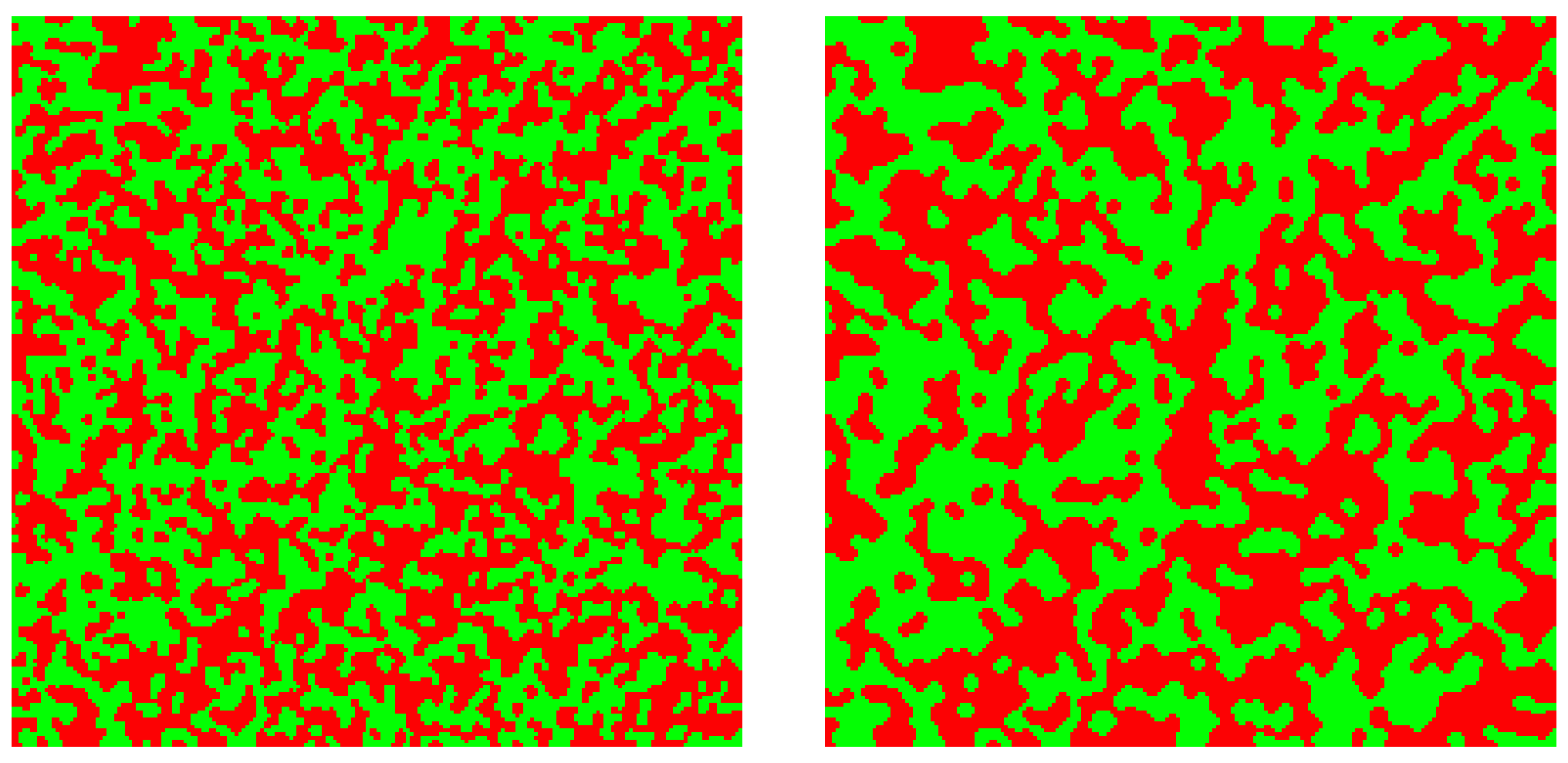
SMR ω-scans taken at 295 K on a MgO(001)/[^{57}Fe(2.6 nm)/Cr(1.3 nm)]$_{20}$ ML evidence ripening in a decreasing external magnetic field between 200 and 100 mT (left figure). The experimental diffuse scatters are fairly well reproduced by a full Distorted-wave Born approximation (DWBA) calculation [3] supposing an exponential shape of the lateral autocorrelation function of the magnetisation with correlation lengths ξ = 600 nm and 1000 nm before and after ripening, respectively (right figure).

Cellular-automaton-based Monte Carlo simulation of ripening



1	2	3
8	?	4
7	6	5

Elementary decision of a pixel in the Monte Carlo simulation.



Cellular-automaton-based Monte Carlo simulation of domain patterns of an AF-coupled ML in decreasing magnetic field before (left) and after (right) ripening.

Monte Carlo simulation

The Monte Carlo simulation based on a cellular automaton algorithm starts with generating random values of $H_S(\mathbf{r})$ on the pixel lattice. The DW energy of the ML is calculated as the sum of the next-neighbour pixel DW energies with non-vanishing contribution only from pairs of opposite SOR of the top-layer magnetisation. The next-neighbour DW energy E_{wall} is supposed to be proportional to the square of the DW angle 2ϑ with a coupling coefficient D having no lateral distribution: $E_{wall} = 4\,D\,\vartheta^2$. Should a pixel jump from one SOR to the other, half of its full hysteresis loss, i.e., $2H_CM\sin\vartheta$ will be dissipated (H_C is the coercivity of the ferromagnetic layers considered to be constant for the whole ML). The movies of the domain dynamics with varying H or T (i.e., H_C) shown in an adjunct computer demo consist of pictures. Subsequent pictures of the calculation always differ from each other only by the SOR of a single pixel (the saturation state being considered to have a third, 'neutral' SOR). On gradually changing H or H_C, a pixel will change its SOR if the new state, taken into account the DW energy and the hysteresis loss, will be energetically more favourable (the bilinear layer-layer coupling and the Zeeman energy do not change during the SOR jump). Thus the simulation depends from D and H_C only through their ratio D/H_C. The simulation of domain ripening reproduces the observed, relatively sudden transition. This is attributed to the fact that the pixel model properly accounts for the local character of the DW interaction. Therefore ripening is seen in the movies as a smoothing out of the DWs and vanishing of small enclosures of the opposite SOR. The autocorrelation functions resulting from the simulation are nearly of exponential shape their correlation lengths ξ increasing by a factor 1.37 during ripening. This is in fair agreement with the experimentally observed factor 1.67 (ξ = 600 nm and 1000 nm before and after ripening, respectively).

Conclusions

The Monte Carlo simulation based on the rough pixel model and a cellular automaton algorithm turns out to describe surprisingly well all features of domain ripening. Domain ripening is associated with smoothing of the domain walls rather than with their long-range movement, a consequence of the short-range interaction of the pixels mediated by the domain walls. The shape of the diffuse SMR scatter both before and after ripening is well reproduced by a DWBA calculation supposing an exponential lateral autocorrelation function of the layer magnetisation. The exponential autocorrelation function and the change of the correlation length are supported by the Monte Carlo simulation.

Acknowledgements

We gratefully thank D. Aernout, B. Croonenborghs, B. Degroote, J. Dekoster, T.H. Deschaux-Beaume, O. Leupold, C. Strohm, J. Swerts and V. Vanhoof for their valuable contribution. Provision of synchrotron radiation by the European Synchrotron Radiation Facility, Grenoble is highly acknowledged. This work was supported by the European Community via STREP No. NMP4-CT-2003-001516 (DYNASYNC) and the grant No. T047094 of the Hungarian Scientific Research Fund (OTKA).

References

[1] M. Rührig et al., Phys. Status Solidi A 125 (1991) 635.
[2] D.L. Nagy et al., Phys. Rev. Lett. 88 (2002) 157202.
[3] L. Deák et al., Phys. Rev. B 76 (2007) 224420.