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- fill in a separate form for each project or series of measurements.
- type your report, in English.
- include the reference number of the proposal to which the report refers.
- make sure that the text, tables and figures fit into the space available.
- if your work is published or is in press, you may prefer to paste in the abstract, and add full reference details. If the abstract is in a language other than English, please include an English translation.

ESRF	**Experiment title:** X-ray study of spintronic transistor structures fabricated in inhomogeneously strained IIIMnV ferromagnetic semiconductors	**Experiment number**: SI-1694
Beamline: ID10B	**Date of experiment**: from: 30.4.2008 to: 5.5.2008	**Date of report**: 15.8.2008
Shifts: 15	**Local contact(s)**: Jiri Novak	*Received at ESRF:*

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Report:

It has been demonstrated recently that it is possible to locally tune and control spin-orbit coupling induced magneto-crystalline anisotropies in (Ga,Mn)As and, consequently, to tune the derived magneto-transport and micromagnetic characteristics [1-3]. This is achieved by lithographically producing strain relaxation and the effect is found to be sensitive to the carrier concentration and to other parameters of the (Ga,Mn)As ferromagnetic semiconductor material. In order to verify this concept, we have performed a series of SQUID measurements of the magnetic anisotropy of litographically patterned surface gratings in pseudomorph epitaxial GaMnAs layers deposited by molecular beam epitaxy onto GaAs(001) substrates.

Due to the lattice mismatch between the GaMnAs epitaxial layer and the GaAs substrate underneath (produced mainly by Mn atoms in interstitial positions), the layer is biaxially elastically strained. Using electron beam lithography and reactive ion etching, we have prepared a periodic pattern of wires on the GaMnAs surface, with the period of 2 μm and the width ratio wire:groove of 1:1. The wire direction was [-110] or [010]. The strain distribution in the layer is then affected by lateral elastic relaxation in the GaMnAs layers, which influences the magneto-crystalline anisotropy.

The task of the x-ray measurements was to investigate the two-dimensional distribution of elastic strain in the GaMnAs wires and in the GaAs substrate in the vertical (-110) or (010) plane *xz* perpendicular to the wire direction. We have measured a series of reciprocal-space maps of x-ray intensity diffracted in coplanar diffractions 004 (symmetric) and 224 or 404 (asymmetric, grazing exit), the scattering plane was always perpendicular to the wire direction. We used the primary beam with the energy of 7.95 keV, the angular resolution of the setup was improved by using a Si111 analyser crystal in front of the detector.

We have investigated a series of 6 samples; samples denoted C077#n (n=10,11,12) have been fabricated on a GaMnAs layer with the nominal lattice mismatch $f = 9\times10^{-4}$, samples C127#n (n=10,11,12) have been prepared on the layer with $f = 3.6\times10^{-3}$. The samples differ in the heights of the etched wires. In samples n=10,11 the wires were oriented along [-110], samples n=12 have the wires along [010].

The reciprocal-space distribution of diffracted intensity exhibited a series of periodic lateral satellites along the q_x axis, the period of which was $2\pi/L$. Since the periodicity of the wires produced by the lithography procedure was almost perfect, the shapes of individual satellites depend only on the resolution function of the diffractometer and for the determination of the strain distribution in the wires only the integrated intensities of the satellites are important. The wire period was quite large so that the angular distance of the satellites was comparable to shortest angular stepsize. This is demonstrated in Fig. 1 presenting a lateral q_x scan of sample C127#12 in diffraction 004. The lateral satellites are extermely narrow and it is quite difficult to obtain correct intensities of the satellites. In order to obtain right values of integrated intesities of the satellites, we have intentionally degraded the angular resolution using the crystal analyzer in the dispersive position. Then, we have not resolved individual satellites, but the intensity distribution correctly represented the integrated intensities of the satellites.

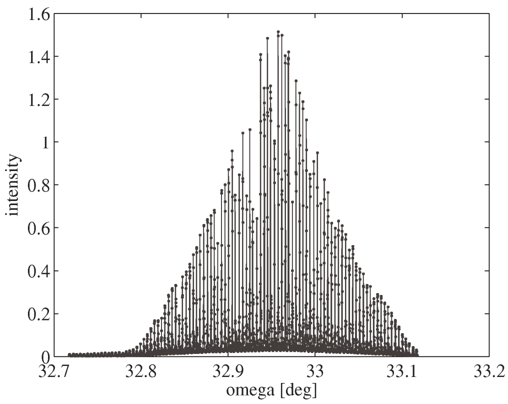

Fig. 1 Lateral scan of sample C127#12, 004 symmetrical diffraction, high angular resolution

The intensity distributions measured in symmetric 004 and asymmetric 224 or 404 diffractions were compared to numerical simulations. Based on the shape of the wire cross-section obtained from scanning electron microscopy (SEM) we have calculated the elastic strains in the wires and in the substrated using continuum elasticity and the finite-element method. The calculated strain fields have been used for the simulation of the scattered intensity, for this simulation we used kinematical approximation. The resulting reciprocal-space distribution of scattered intensity was compared with the experimental data. In order to achieve a better match, we have modified the shape of the wire cross-section to trapezoidal one. The difference between the wire morphology following from SEM and the wire shape yielding the best match of the simulated and measured intensity maps, can be ascribed to the presence of a highly damaged surface layer caused by reactive ion etching that does not contribute to the diffracted intensity.

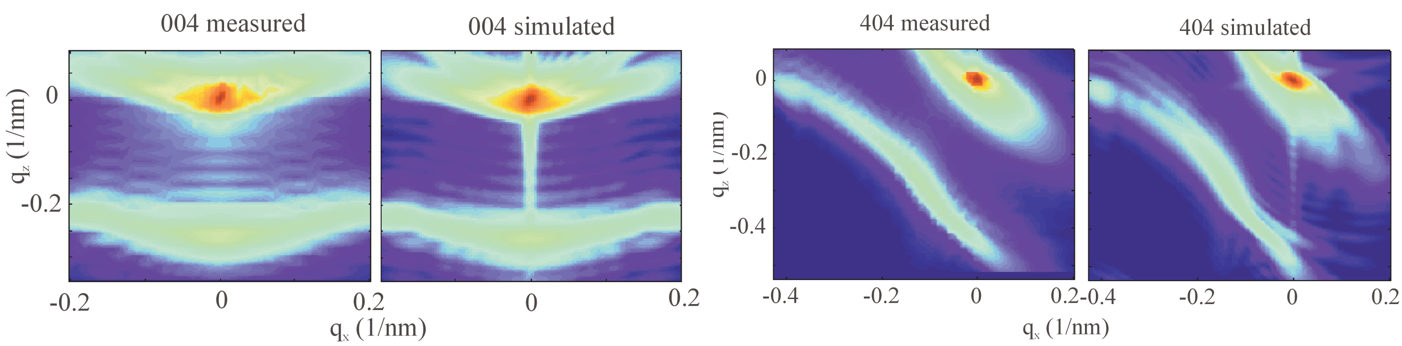

Fig. 2 Measured and simulated reciprocal-space maps of sample C127#12, symmetric diffraction 004 (left) and asymmetric 404 (right panels). The step of the intensity contours is $10^{0.2}$.

As a representative example, we show the results of the sample C127#12. Figure 2 presents the measured and simulated reciprocal space maps in symmetric 004 and asymmetric 404 diffraction, the scattering plane (010) is perpendicular to the wires oriented along [010]. The measured reciprocal space maps do not exhibit lateral satellites, since the angular resolution used was not sufficient to resolve them. Therefore, the lateral distance between the wires is larger than the effecitve coherence width of the primary radiation and the neighborimng wires are irradiated incoherently.
From the figure it follows that the agreement between the measured and simulated intensity distributions is almost perfect. In order to achieve such a match we have to modify the wire cross-section, we have assumed a trapezoidal cross-section and we have optimized the upper and bottom width of the wires. Figure 3 shows the elastic displacement field calculated using the finite-element method; this displacement field was used for the

calculation of the scattered intensity in Fig. 2. The lattice mismatch between the GaMnAs layer and the GaAs substrate was determined to $f = (3.75 \pm 0.02)\times10^{-3}$.

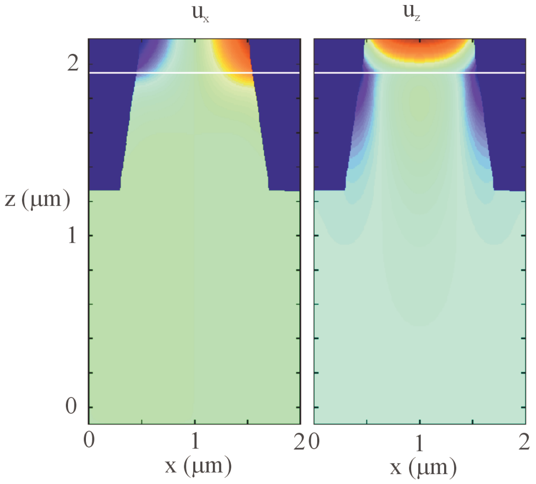

Fig. 3 Distribution of the horizontal (left) and vertical (right) component of the elastic displacement vector obtained by a finite-element mothod simulation. The horizontal white line denotes the GaMnAs/GaAs interface, the contour step is 0.01 nm.

Summarizing, we have successfully determined the elastic strain and elastic strain relaxation in lithographically patterned ferromagnetic GaMnAs wires. The resulting displacement field will be used as an input for ab-initio simulations of magneto-crystalline anisotropy and the simulated magnetic hysteresis curves will be compared with SQUID measurements. The results will be published in near future.

[1] J. Wunderlich, A. C. Irvine, J. Zemen, V. Holý, A. W. Rushforth, E. D. Ranieri, U. Rana, K. Výborný, J. Sinova, C. T. Foxon, et al., Phys. Rev. B **76**, 054424 (2007).

[2] S. Hümpfner, M. Sawicki, K. Pappert, J. Wenisch, K. Brunner, C. Gould, G. Schmidt, T. Dietl, and L. W. Molenkamp Appl. Phys. Lett. **90**, 102102 (2007).

[3] K. Pappert, S. Hümpfner, C. Gould, J. Wenisch, K. Brunner, G. Schmidt, and L. W. Molenkamp Nature Physics **3**, 573 (2007).