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Lorentz Phase Imaging and In-situ Lorentz Microscopy of Patterned Co-Arrays.

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Understanding magnetic structures and properties of patterned and ordinary magnetic films at nanometer length-scale is the area of immense technological and fundamental scientific importance. The key feature to such success is the ability to achieve visual quantitative information on domain configurations with a maximum 'magnetic' resolution. Several methods have been developed to meet these demands (Kerr and Faraday effects, differential phase contrast microscopy, magnetic force microscopy, SEMPA etc.). In particular, the modern off-axis electron holography allows retrieval of the electron-wave phase shifts down to $2\pi/N$ (with typical N =10-20, approaching in the limit $N\approx100$) in TEM equipped with field emission gun, which is already successfully employed for studies of magnetic materials at nanometer scale. However, it remains technically demanding, sensitive to noise and needs highly coherent electron sources.

As possible alternative we developed a new method of Lorentz phase microscopy [1,2] based on the Fourier solution [3] of magnetic transport-of-intensity (MTIE) equation. This approach has certain advantages, since it is less sensitive to noise and does not need high coherence of the source required by the holography. In addition, it can be realized in any TEM without basic hardware changes. Our approach considers the electron-wave refraction in magnetic materials (magnetic refraction) and became possible due to general progress in understanding of noninterferometric phase retrieval [4-6] dealing with optical refraction. This approach can also be treated as further development of Fresnel microscopy, used so far for imaging of in-situ magnetization process in magnetic materials studied by TEM.

Figs. 1-3 show some examples of what kind information can be retrieved from the conventional Fresnel images using the new approach. Most of these results can be compared with electron-holographic data. Using this approach we can shed more light on fine details of in-situ magnetization process in magnetic materials and films studied by TEM. As an example, Fig.4 illustrates the evolution of domain configurations in 25-nm thick Co-elements patterned on silicon nitride membrane as function of applied field, ranging from +70 to -70 Oe. The Lorentz phase microscopy allows better understanding the role of magnetization ripple (41 Oe) in nucleation of reverse domains (28 Oe), or vortex formation (-4.4 Oe) followed by the reverse domains expansion and final annihilation of domain walls (41/-41 Oe) at the sample edges.

It is believed that due to technical simplicity the Lorentz phase microscopy will find more applications in the nearest future.

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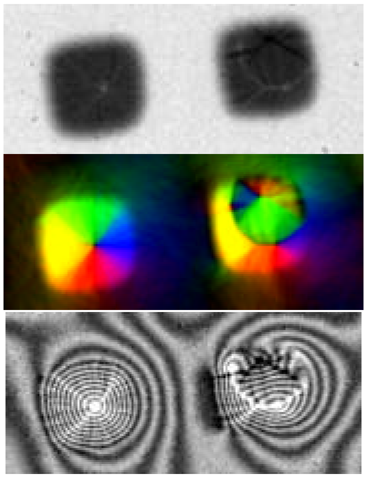

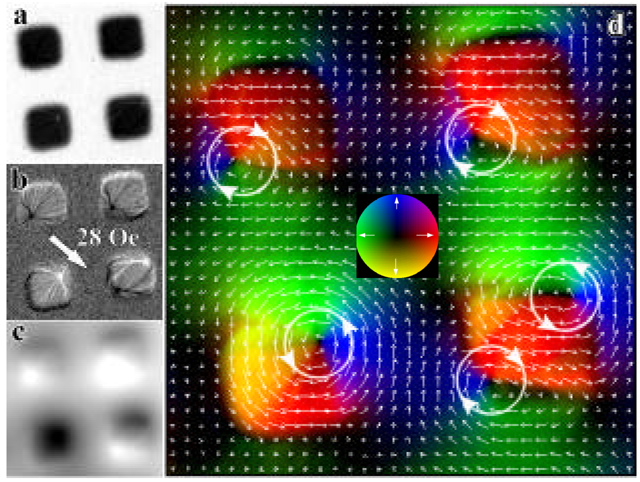

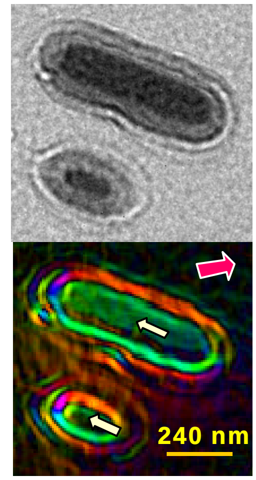

Fig. 1 Lorentz phase imaging of 25 nm thick patterned Co-islands of 6 μm size observed at zero field (left): experimental defocused image (top), projected induction tB-map (middle) and magnetic flux distribution (bottom) for couple of Co-elements with closure domain structure, retrieved by MTIE-solution.

Fig.2 Lorentz phase imaging of patterned magnetized Co-islands recorded at 28 Oe of in-plane magnetic field (middle): (a) experimental defocused image, (b) z-gradient of intensity, (c) phase retrieval and (d) projected induction map displayed by the color code given on the inset.

Fig.3 Direct test of magnetic recording (right): experimental image (top) and single bit of magnetic information (observed as green-color area at the bottom) recorded in elements of 150x240 and 260x560 nm^2 size, while the red-color arrow shows the direction of applied field.

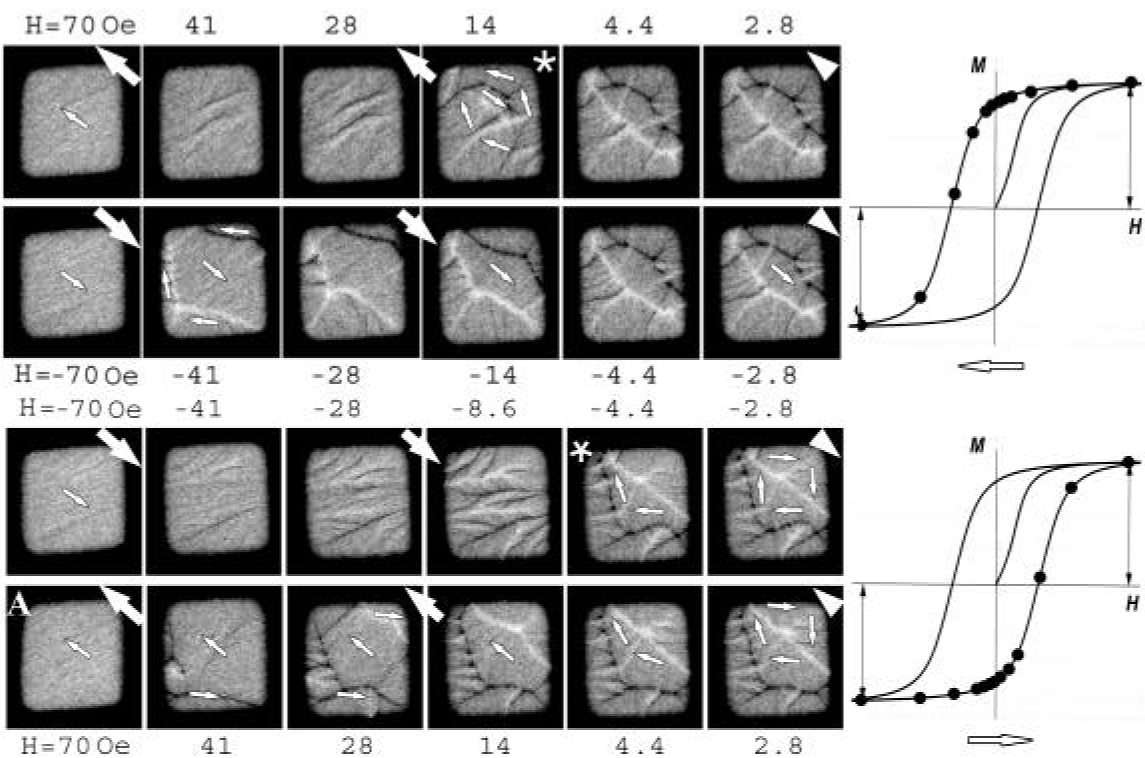

Fig. 4 In-situ Lotentz observations of magnetization process in 6 μm size patterned Co-islands versus applied field, shown by large arrows. Still images on top were recorded by CCD and reflect fine details of domain configurations versus decreasing (70 → -70 Oe) field, while images at bottom correspond to opposite process, given by the lower part of the same hysteresis loop, shown on the right.

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