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Magnetic Induction Mapping in TEM of Micro- and Nano-Patterned Co/Ni Arrays

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Understanding magnetic structures and properties of patterned magnetic films at nanometer length-scale is the area of immense technological and fundamental scientific importance. The patterned magnetic films can be used for magnetic sensing applications, magnetic recording, magnetoelectronics, microactuators and hybrid magneto-supercondicting devices. The optimization of film properties is crucially dependent on the understanding of their magnetic properties, which in turn, become sensitive to the specific geometry and, hence, magnetic configurations of a given system when the elements diminish in size.

Recent progress in the field of noninterferometric phase retrieval bring the ordinary Fresnel microscopy to a new quantitative level, capable of recovering both the amplitude and phase of the object from the experimental images [1, 2], and thus induction mapping of small magnetic elements with known geometry ranging from micro- to few nanometers in size. The key concept behind this approach is the improvement of phase recovery algorithm derived from the *transport-of-intensity* (TIE) equation with a fast-solution via Fourier transform. A number of quantitative in-situ TEM magnetization experiments can be realized now with the help of magnetic-field calibrated microscope (see, for example [3]).

To demonstrate the practical use of the new approach in TEM magnetic imaging with nanoscale resolution we have prepared several films directly on 3mm TEM-grids: (a) square-patterned magnetic films of Co islands with size of 6 μm (Fig. 1), and (b) nano-patterned arrays of Ni-nanodots (Fig.2) with lateral size about 40nm. The Co-films were prepared in UHV system by electron-beam evaporation of Co through an appropriate mask onto 30-nm-thick Si_3N_4 membrane. The thickness of magnetic elements was approximately 40 nm as determined by EELS. The array of Ni-nanodots on a carbon membrane was prepared by electron-beam TEM-nanolithography followed by oblique angle deposition. Both types of the patterned arrays for Co and Ni films have been characterized by the TEM/ED methods. They were found to have a polycrystalline microstructure with the average crystallite size ~10 and 7 nm respectively. The Co films consisted of mixture of cubic and hcp phases.

To experimentally check the sensitivity of TIE-recovered phase information to local magnetic configurations a set of in-focus and out-of-focus images was recorded on CCD (1kx1k) during the *in-situ* magnetizing experiments in JEOL3000F microscope at different magnifications using the Gatan Imaging Filter (GIF) as function of applied field (H) and/or specimen tilt angle (φ) under constant external field. The results of the image processing (Figs.1-2), strongly suggest that TIE-phase retrieval method is a powerful tool suitable for local induction mapping B(x,y) of in-plane magnetization of magnetic elements down to few nanometers scale. The method is fast, robust, insensitive to noise, does not require the holographic equipment, and can be applied to a wide class of objects. The quantitative results can be obtained for films of known or uniform thickness.

References:
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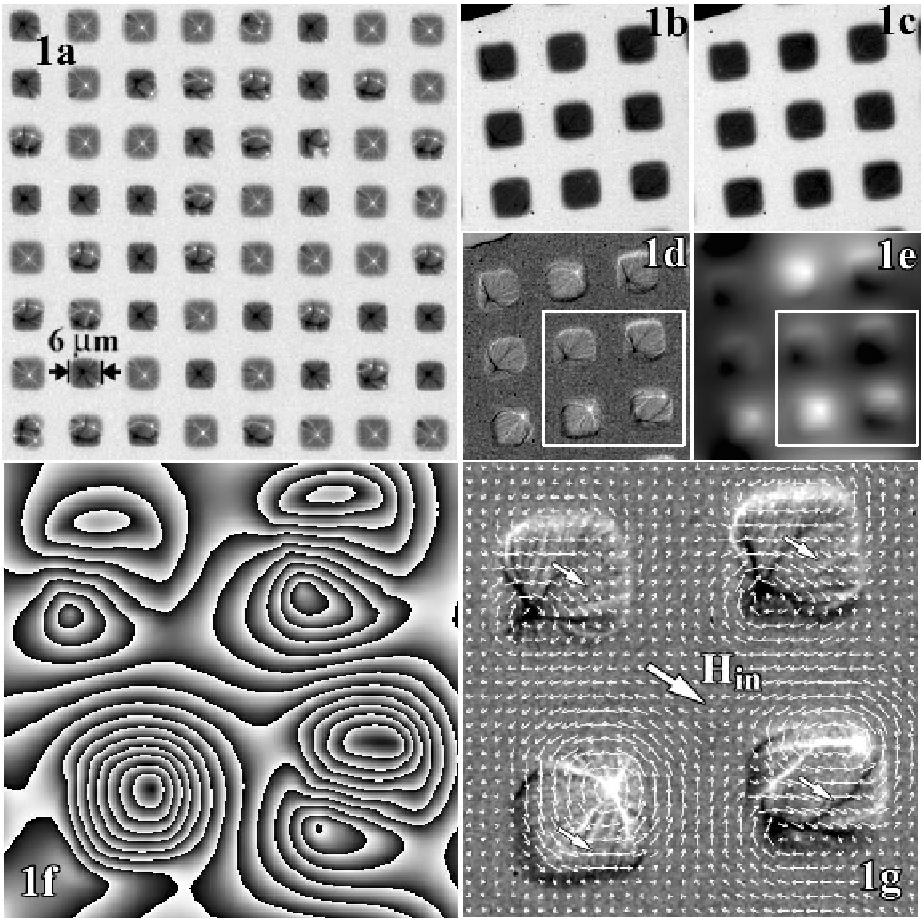

Fig.1 Results of image processing using TIE-phase retrieval algorithm: (1a) low magnification Fresnel image of patterned 2D-array of Co islands; (1b-1c) two defocused images used for phase reconstruction; (1d) pure phase contrast; (1e) recovered phase map; (1f) part of the phase map as potential contours selected from the boxed area of Fig.(1e); (1g) calculated M-vector map (magnetization) for the same boxed area plotted over the phase contrast image (1d). The image (1a) was recorded at H=160 Oe normal to image plane. The other images were recorded at 10 deg. tilt to produce the in-plane component of external field H_{in}=30 Oe (1g).

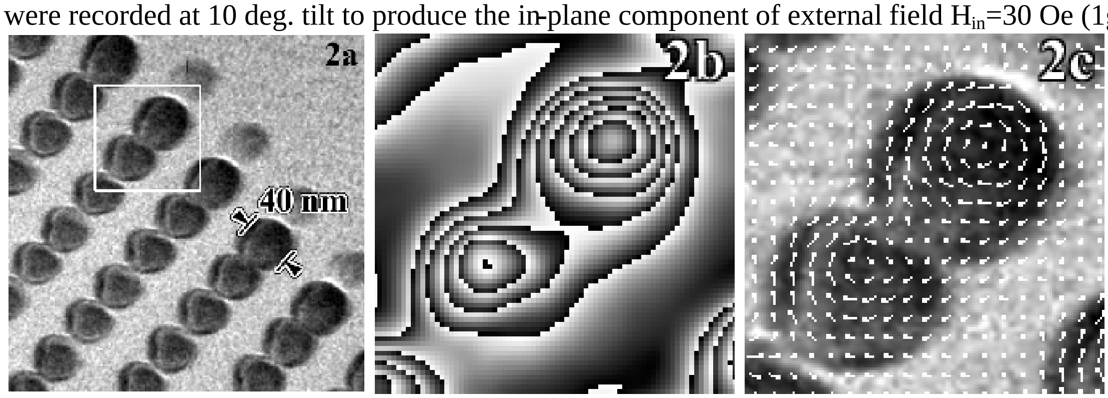

Fig.2 The in-focus image of 2D-array of Ni-nanodots grown on amorphous carbon membrane and viewed in Fresnel Lorentz mode (2a). The size of each nanodot is about 40 nm. Fig. 2b shows the equipotential contours of the reconstructed phase for the boxed area highlighted in (2a). The phase gradient information as M-vector map (magnetizetion) is shown in Fig. 2c.

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