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Observation of Magnetic Lines of Force by Electron Phase Microscopy

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Electron phase microscopy has been used to illuminate fundamental phenomena in magnetism and superconductivity by visualizing quantitative magnetic lines of force.

Although electrons are always detected as particles, they also show wave properties. We can now practically use the wave nature of field-emission electrons to directly image the quantum world by obtaining the phase information of electrons [1]. Projected magnetic lines of force can be quantitatively observed as phase contours of transmitted electrons by using holographic interference microscopy [2] based on the Aharonov-Bohm (AB) effect principle [3], and quantized vortices in superconductors can be dynamically observed by Lorentz microscopy [4].

We experimentally observed the magnetic fields of magnetic heads and superconductors using 1-MV and 300-kV field-emission transmission electron microscopes. An example of tiny magnetic heads is shown in FIG. 1. The head is used for high-density perpendicular recording. It must produce a very high and yet localized magnetic field. However, this is not sufficient. For example, we also need a zero field outside the head in some cases.

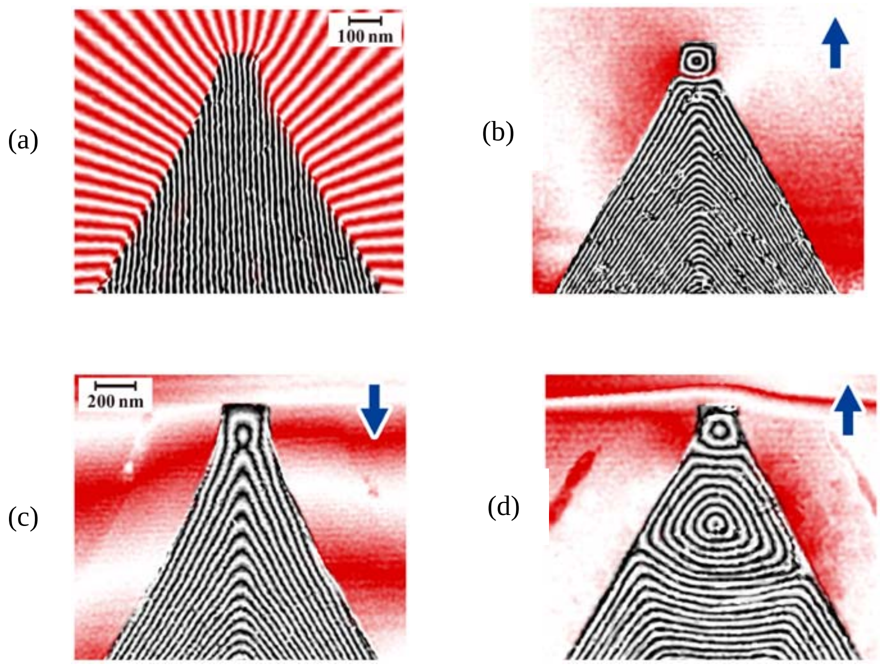

FIG. 1. Interference micrographs showing magnetic lines of force of magnetic heads for perpendicular recording: (a) H = 80 Oe (NiFe); (b) H = 0 (NiFe) after the upward magnetic field; (c) H = 0 (NiFe) after the downward magnetic field; (d) H = 0 (CoNiFe).

In the case of an FeNi head, straight magnetic lines inside the head (FIG. 1 (a)) were changed to “U-turn” lines [5] (FIG. 1 (b)) when the applied magnetic field was reduced from 80 Oe to zero. At the pole tip, the magnetic lines formed a tiny closed circuit, creating vanishing leakage fluxes outside the head. This remanent state is reversible but slightly dependent on the previously applied magnetic field (see FIG. 1 (c)). Hysteresis became noticeable when the head material was changed from FeNi to CoNiFe (see FIG. 1 (d)).

We also observed the nucleation and growth of ferromagnetic domains in colossal magnetoresistance materials, in which an electric current begins to flow when the magnetic field increases or the temperature decreases. The microscopic mechanism for this is considered to be the fact that isolated tiny ferromagnets nucleate and coalesce in the “insulating” phase, thereby creating conduction paths of electrons. We investigated this directly using Lorentz microscopy and interference microscopy [6].

The growth of ferromagnetic domains was dynamically observed by Lorentz microscopy (FIG. 2 (a)) while reducing the sample temperature. Interference microscopy revealed that “sepia” leakage flux, as shown in FIG. 2 (b), assisted the domain growth.

References

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(a)

(b)

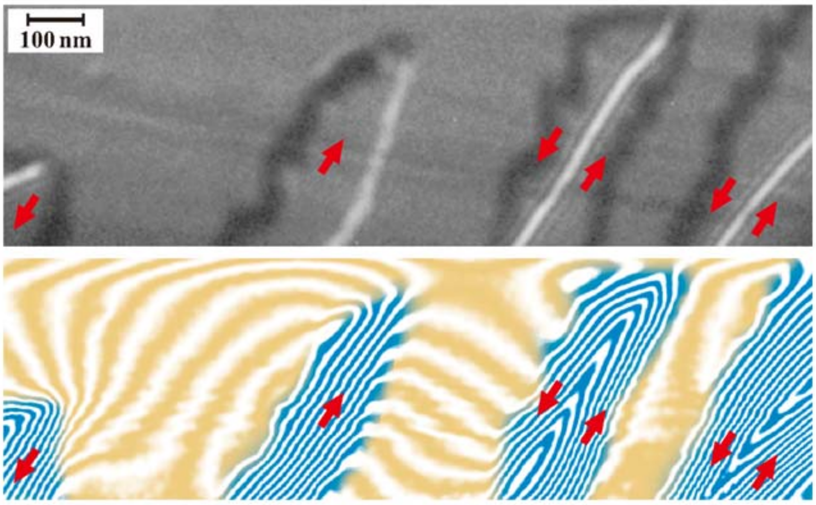

FIG. 2. Growth of ferromagnetic domains in colossal magnetoresistance manganite, $La_{0.25}Pr_{0.375}Ca_{0.375}MnO_3$, thin film at T = 62.4 K: (a) Lorentz micrograph; (b) interference micrograph.