Direct Observation of Fine Structure of Magnetic Domain Walls by Electron Holography

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Holographic interference electron microscopy is presented for investigating the structure of domain walls in plate-shaped cobalt particles. Circular magnetic lines of force are directly observed as contour fringes which overlap individual particle micrographs. These fringes show at a glance how the spin rotates across domain walls. It is also suggested from holographic electron diffraction that the spin stands up in the center of the particle.

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The fine structure of a domain wall in a ferromagnetic thin film plays an important role in determining the fundamental characteristic of the film. However, only a limited number of experimental investigations have been reported, in contrast to many theoretical calculations of wall structures. This is because magnetization cannot be quantitatively measured even by Lorentz microscopy, which has been the only effective method for observing the fine structures of magnetic domain walls to date.

A new method has been developed for observing magnetization in thin films. In this method, the phase distribution of electrons transmitted through a specimen is observed as a contour map by means of holographic interference electron microscopy.[1] Although the electron phase itself is not uniquely determined, the phase difference $\Delta\Phi$ between two points P_1 and P_2 in the specimen plane is given by the following equation[2]:

$$\Delta\Phi(P_1, P_2) = (e/\hbar)\int \vec{B}\cdot d\vec{S}. \quad (1)$$

Here the integral is performed over the surface enclosed by the two electron trajectories passing through points P_1 and P_2. From this equation, an important result is deduced. The phase difference is equal to zero if P_1 and P_2 lie along a magnetic line of force in the film. Therefore, magnetic lines of force can be directly observed as a contour map of the electron wave front by means of electron holography.[3,4] The holographic method for magnetization measurement was first proposed by Cohen.[5] However, no practical results have been reported except some preliminary experiments.[6-8]

Electron holograms were formed in a newly developed field-emission electron microscope.[9] The schematic diagram is shown in Fig. 1. An object is illuminated with a collimated electron beam and its image is formed through the objective lens. A reference beam is projected on the image plane by a Möllenstedt-type electron biprism,[10] forming the off-axis image hologram. The total magnification in the electron microscope was 40 000 times. The electron accelerating voltage was 80 kV.

Reconstruction was carried out in the optical system shown in Fig. 2, where phase-amplification technique was employed for detailed observation.[11] Laser beams A and B illuminate the hologram and each beam produces a reconstructed image and its conjugate, whose phase distributions are opposite in sign. Only the reconstructed image of beam A and the conjugate

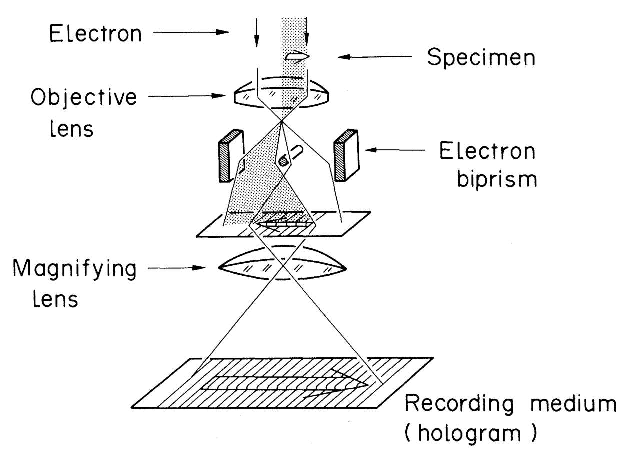

FIG. 1. Schematic diagram of hologram formation.

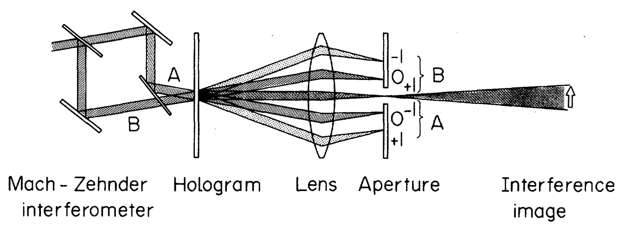

FIG. 2. Schematic diagram of optical reconstruction.

image of beam *B* pass through an aperture and an interference image with a doubled phase distribution is formed. The background of the interferogram is even when the interfering beams travel in the same direction, but a slight tilt between them produces a reference system of regular fringes over the background.

Cobalt specimens[12] were prepared by gas evaporation in a 10-Torr inert gas atmosphere. The particles studied are plate shaped and have $\{111\}$ surfaces and $\langle 110 \rangle$ edges.

Interference micrographs of a triangular cobalt particle are shown in Fig. 3. No contrast is observed inside reconstructed image (a), which is equivalent to the electron microscopic image. On the other hand, many contour lines appear in contour map (b). Contour lines parallel to the three edges show that thickness increases linearly to 55 nm. The inner contour lines are magnetic lines of force, since the inner region is uniform in thickness due to the typical crystal habit of fcc particles.[13] This was also ascertained by observing the extinction contour lines in the electron microscopic image of the particle in which Bragg reflection was excited. The effect of stray field was estimated to be small from the contour map, showing that the magnetic field was closed inside the particle image.

The contour lines in Fig. 3(b) clearly show how the spin direction rotates across the three domain walls. It cannot be determined from this contour map whether the magnetization rotates clockwise or counterclockwise. The direction can be decided from interferogram (c) obtained by changing the angle between beams *A* and *B* in the reconstruction stage. Interference fringes are displaced downward at particle edges and they go further downward inside the particle. This can be interpreted as follows. As an electron beam travels faster in the crystal than in vacuum and consequently has a shorter wavelength, the wave front of the transmitted electron beam through the particle is retarded. Furthermore, the wave front is either advanced or retarded depending on whether magnetization is clockwise or counterclockwise, as known from Eq. (1). Therefore, the magnetization direction proves to be counterclockwise. Particles with clockwise magnetization were also observed. These two kinds of particles have already been observed by Lorentz microscopy.[14]

The magnetization rotation distribution across a domain wall was measured from the contour map. The measured value corresponds to the average magnetization over a film thickness. Wall width obtained was 40 nm.

From the contour map [Fig. 3(b)], magnetization was found to be circular in the central part of the particle. However, it is not reasonable to consider that the spin still remains circular in the extreme center. This is because exchange energy increases infinitely with this magnetization configuration. It is speculated that the spin stands up, but this has not been supported by experimental evidence.

In order to clarify spin behavior in the center of triangular particles, low-angle electron dif-

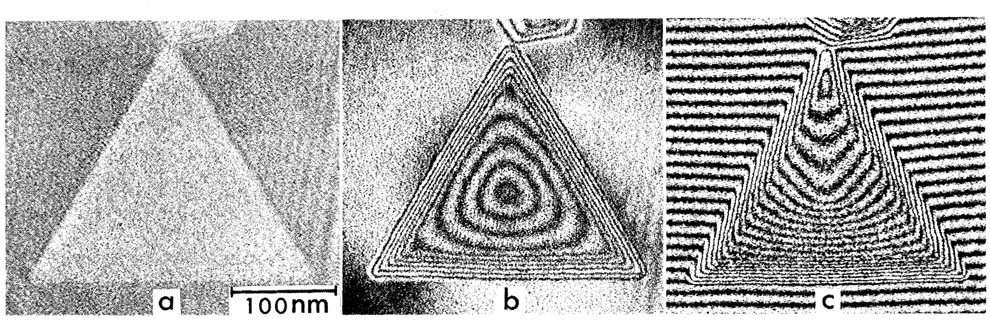

FIG. 3. Triangular cobalt particle: (a) reconstructed image, (b) contour map, and (c) interferogram. Contour lines in contour map (b) are magnetic lines of force. Magnetization direction is counterclockwise from interferogram (c).

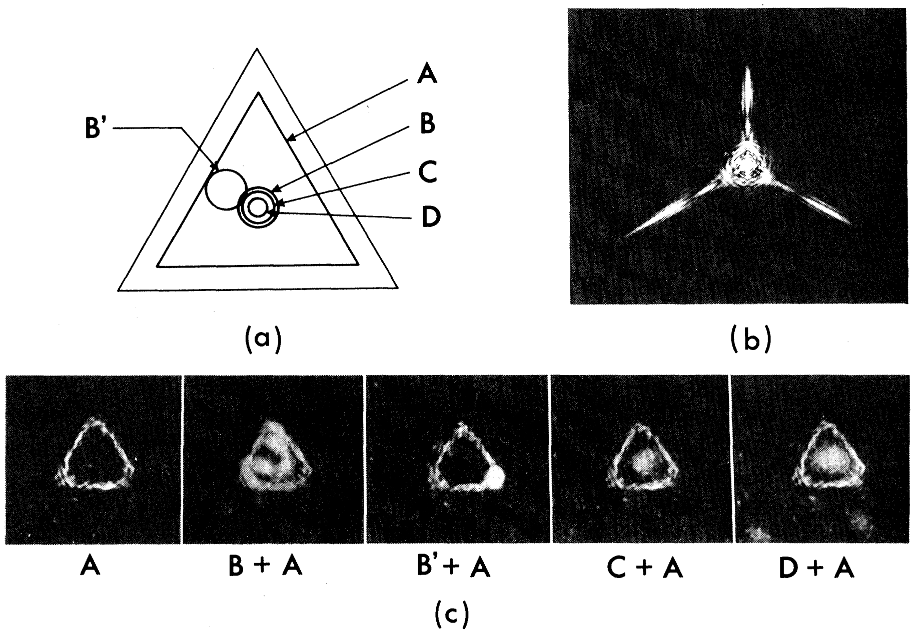

FIG. 4. Low-angle electron diffraction patterns from areas in a triangular cobalt particle: (a) selected areas, (b) diffraction pattern from the particle, and (c) diffraction patterns from selected areas. Diffraction patterns from areas A and B consist of three deflection spots corresponding to the three magnetic domains. However, a single spot appears in diffraction patterns from central areas less than 15 nm in radius (C and D). These results suggest that the spin stands up in the center.

fraction patterns were obtained from the central regions as shown in Fig. 4. These diffraction patterns were optically formed from holograms, since electron holography can reproduce all the information provided by electron beam scattering. The three streaks in diffraction pattern (b) correspond to the three peripheral regions (wedges) of the particle. Actually the streaks are absent in the electron diffraction patterns from the inner region excluding the peripheral wedges as shown in Fig. 4(c). The selected areas are designated A, B, B', C, and D in Fig. 4(a). The radii of selected areas B, C, D are 20, 15, and 10 nm, respectively, and are superimposed over the diffraction pattern from region A to make precise location measurement possible. A diffraction pattern from a large area such as region A consists of three diffraction spots and streaks connecting them. The three spots are due to the three magnetic domains. Actually the measured angle between the center and one vertex of the triangle structure in Fig. 4(c) is 1.4×10^{-4} rad. This agrees fairly well with the calculated deflection angle of 1.1×10^{-4} rad assuming a spontaneous magnetization of 1450 Oe and particle thickness of 55 nm. In the case of selected area B, three spots are still observed. When the areas become smaller, as C and D, only one spot is observed in the center of the triangle. A diffraction effect becomes appreciable with decreasing areas. However, if the area of B is moved to another location, B', in one of the magnetic domains, the diffraction pattern becomes a single spot situated at a vertex of the triangle. This was also true for both areas C and D. In addition, the diffraction spots for areas C and D are not so widely spread as to cover the triangle structure. Therefore, it can be concluded that few electrons are deflected in regions C and D, and that the measured magnetization component in the specimen plane is smaller than the spontaneous magnetization.

These results support the assumption that the spin stands up in the center and furthermore give the information that the area where the spin stands up is less than 15 nm in radius. This is also consistent with the interferogram in Fig. 3(c), which indicates that the electron wave front is not pointed in the center, but curved in a central region about 10 nm in radius.

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Polarization of the Primeval Radiation in an Anisotropic Universe

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The results are given of accurate computations of the polarization of the cosmic microwave background radiation in homogenous anisotropic universes with flat spacelike hypersurfaces. The degree of polarization never exceeds twice the maximum temperature quadrupole anisotropy, and its value is found to be very sensitive both to the mass fraction in the form of hydrogen and to its ionization history. There is no spectral distortion to first order.

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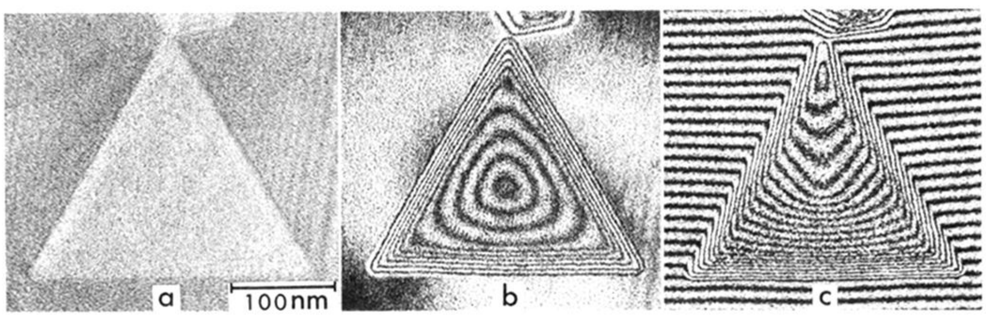
Meausrement of the polarization of the cosmic microwave background radiation, generally considered to be the relict radiation from the big bang, can set important constraints on the possible anisotropy of the universe. Other properties of the radiation, such as its large-scale isotropy[1] and blackbody spectrum,[2] have generally tended to confirm the standard big-bang interpretation. The observed dipole temperature is generally assumed to be due to the motion of the earth relative to the cosmological frame of reference. However, anisotropic cosmological models could in principle result in a similar effect.[3] Polarization measurements of the cosmic background radiation could provide a unique signature of cosmological anisotropy.[4,5] Moreover, the degree of polarization in an anisotropic universe is very sensitive to its ionization history and to its fractional hydrogen content. We describe below new calculations that correct and extend previous estimates of polarization in anisotropic universes with flat spacelike hypersurfaces (Bianchi type I).

The photon distribution function is assumed to be that of an isotropically radiating blackbody at a sufficiently early epoch. Its subsequent evolution is determined by the collisional Boltzmann equation, the interaction between matter and radiation being determined by Thomson scattering at red shifts $z \lesssim 10^7$. For simplicity, we restrict ourselves initially to axisymmetric homogeneous



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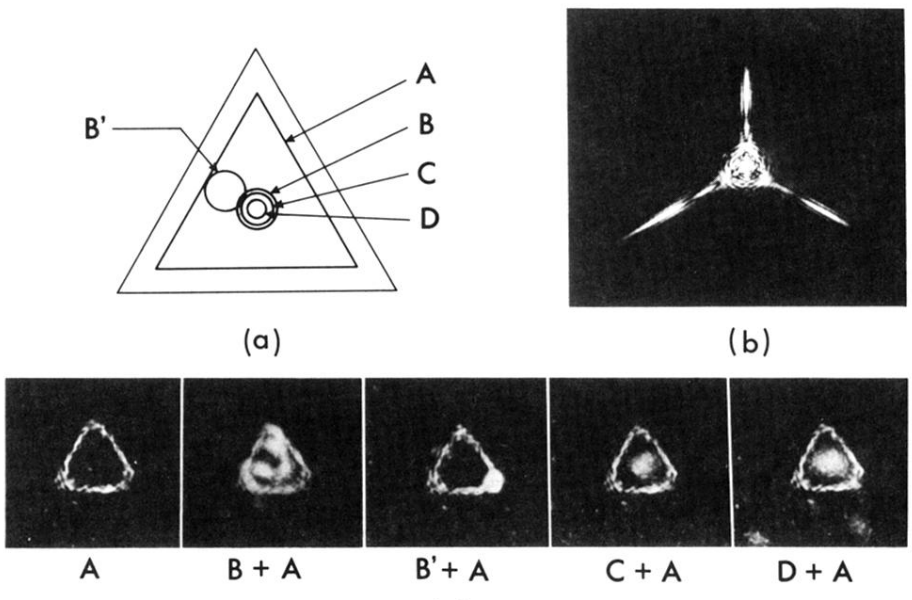

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