Differential microscopy by conventional electron off-axis holography

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Differential microscopy is realized by conventional off-axis electron holography with an electron biprism behind the specimen. Two phase images reconstructed from two holograms which are obtained with slightly different potentials of the electron biprism are utilized to make a one-dimensional differential image. Polystyrene latex particles which are charged by electron irradiation are used to demonstrate that the differential image is independent of the distortion of a reference wave. © *1996 American Institute of Physics.* [S0003-6951(96)00144-1]

A transmission electron microscope (TEM) equipped with a field-emission electron gun and an electron biprism makes it possible to construct an electron holographic interferometer.[1] Especially off-axis electron holography has been successfully used in the observation of phase objects such as magnetic fields[2,3] and electrostatic potentials.[4,5] In off-axis holography a well-defined reference wave is indispensable for making interference fringes. In many cases, however, the magnetic or electric field extends beyond the lateral coherent length of the electrons, which means that only the phase difference between an object wave and the reference wave may be obtained. As a result, the information extracted from the hologram with the distorted reference wave does not accurately express the fields or the potentials of the object. Moreover, for the observation of magnetic substances, a distortion-free or plane reference wave restricts the observation area to the region near the edge of the specimen, although the magnetic structures inside the specimen are also of interest.

One of the ways to surmount this problem of the distorted reference wave has been shown by Matteucci *et al.*[5] Their analysis using a computer simulation reveals an accurate field for some simple cases. Differential interferometry,[6] a typical case of shearing interferometry, is another useful method for observing phase objects when a plane reference wave cannot be obtained.

With regard to electron holographic interferometry, some configurations for differential interferometry have been reported. They illuminate the specimen with two coherent electron beams inclined toward each other by using a beam splitter placed in front of the specimen. Leuthner, Lichte, and Herrman[7] installed an electron biprism in the illumination system of a scanning TEM (STEM) equipped with a detection system that has a reference grating. The resolution of this scanning-type interferometer that has been reported so far is not very high (>5 nm). Mankos, Scheinfein, and Cowley[8] utilized the same configuration for a projection-type differential interferometer, and showed magnetic domains in a Co film. Their interferometer, however, requires intrinsically larger defocusing of the object for a larger interference region. Kruit and Buist[9] used a crystalline beam splitter inserted into a TEM instrument equipped with an ordinary thermionic electron gun. Their technique requires that the crystalline beam splitter has a large uniform area of orientation and thickness, which are both obstacles in practical applications.

On the other hand, in conventional electron off-axis holography,[1] using a TEM instrument (off-axis TEM holography) which has an electron biprism behind the specimen, the interference region is limited by only the lateral coherent length of the electron waves. A resolution higher than that attainable with STEM holography is easy achievable[10,11] with off-axis TEM holography, which has improved the precision of its phase measurement,[12] but sufficiently small shearing of the object wave has been impossible. If two holograms, which have a slight difference in the sheared regions of their object wave by the reference wave, are recorded, then the difference of the waves reconstructed from these two holograms offers shearing interferometry. When the amount of the shearing is sufficiently small, this interfer-

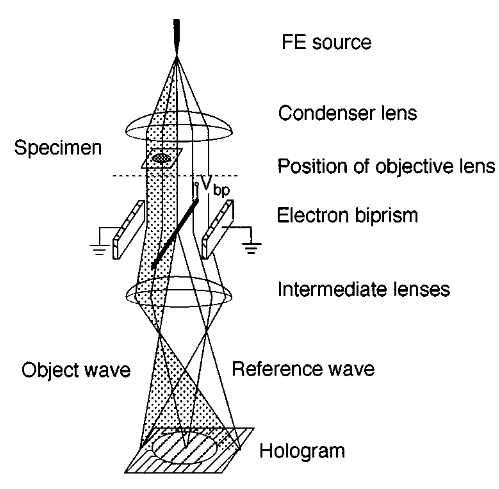

FIG. 1. Schematic electron-optical system for electron holographic interferometry.

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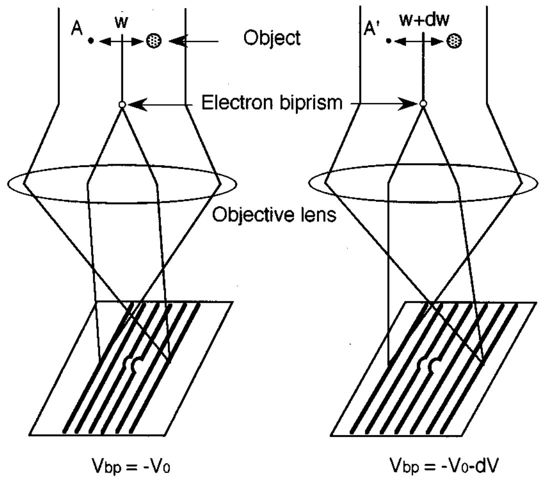

FIG. 2. Reference point overlapped with an object is sheared dw from A to A′ by increasing the potential applied to an electron biprism $-V_0$ to $-V_0\text{-}dV$.

ence pattern corresponds to the differential of the object. In this letter, a preliminary result of differential microscopy by off-axis TEM holography is reported for the electrostatic potential around charged polystyrene latex particles.

Electron holograms are constructed by the interference of a modulated object wave and a reference wave, as shown in Fig. 1. The shearing of the interference region essential for the differentiation is achieved by changing the potential applied to the electron biprism, as illustrated in Fig. 2.

A Hitachi HF-2000 FE-TEM equipped with a Gatan 679 slow-scan charge-coupled-device (CCD) camera was used to make holograms and the processing was performed on a Macintosh personal computer. The objective lens and condenser lenses were turned off, and two intermediate and two projective lenses were excited maximally. The direct magnification was 2000 times on a fluorescent screen. The exposure time was by a mechanical shutter rather than by a magnetic deflector, which is the ordinary system for a Hitachi electron microscope combined with a slow-scan CCD camera. This is essential in electron holography, because source drift, which is due to the time delay of ferrite cores of the deflector coils, causes the initial phase of the electron to drift. Typical exposure time was 20 s and readout time from the CCD to a frame memory was 2 s per frame of 1024×1024 pixels.

Figures 3 and 4 show the differential interferometry of polystyrene latex particles of 1 μm in diameter charged by electron irradiation. The electron wave passing through the region that includes two charged particles [indicated by arrow heads in the low magnification TEM image in Fig. 3(a)] was superimposed using an electron biprism (BP) with $V_{bp} = -13$ V to make a hologram [Fig. 3(b)] in which electric fields around the latex spheres modulate the reference waves. A blank hologram was obtained in the area sufficiently far from any particles under the same biprism condition and was referred to in order to reconstruct a phase image [Fig. 4(a)] from which another phase image [Fig. 4(b)] reconstructed from a hologram recorded with $V_{bp} = -13.5$ V was subtracted. The amount of shearing was about 0.1 μm. The subtraction was performed to keep the coordinates of particle A the same in both reconstructed waves so that the potential around particle B could be differentiated along the lateral direction in Fig. 4(c). If the phase shift along the edge of the differentiated area is sufficiently small, we can integrate the differential image so that the potential distribution free from the effect of the reference wave is revealed, as shown in Fig. 4(d). The dark band in the figure is due to the indeterminable area in the phase that corresponds to particle A, which is opaque for 200 keV electrons. As easily understood from Fig. 3(a), an unsymmetrical distribution of the potential around B means the interaction with particle A, namely, the potential at the side facing particle A, has a larger gradient than that at the other side.

The accuracy of the differential interferometry is determined by the amount of shearing, which is controllable by supplying potential within the detectable limit of phase difference. In practice, however, there were two dominant factors. One was the accuracy of the direction of shearing, which often was not exactly perpendicular the ends of the biprism wire. This problem is especially severe in two-dimensional differentiation. For the integration to obtain a

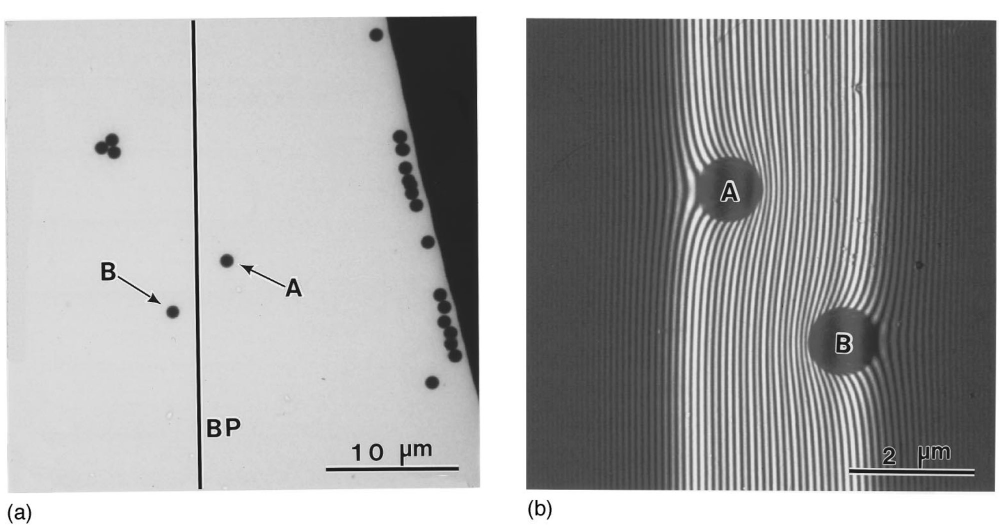

FIG. 3. (a) Low-magnified TEM image of polystyrene latex particles (d=1.0 mm). (b) Two spheres indicated with arrow heads were recorded in an electron hologram from both sides of an electron biprism (BP).

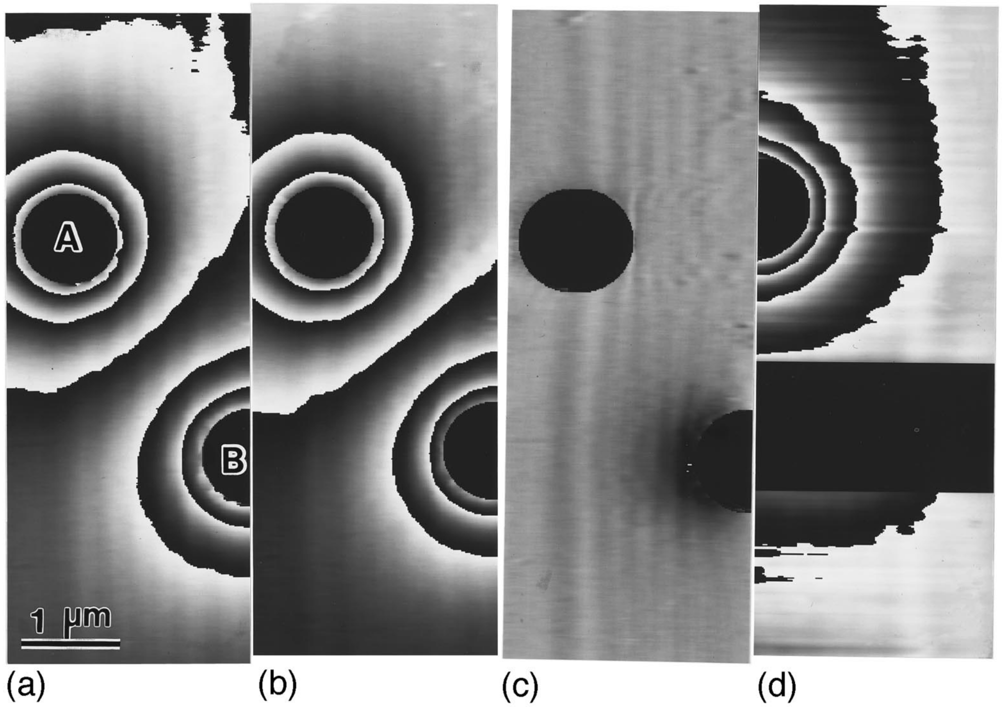

FIG. 4. Differential interferometry of latex spheres. (a) A phase image reconstructed from a hologram taken with the biprism potential $V_{bp}=-13.0$ V; (b) another phase image of $V_{bp}=-13.5$ V; (c) a one-dimensional differential image; and (d) integrated image showing a true phase distribution.

phase distribution like that shown in Fig. 4(d), the reliability of the assumption for the uniform phase angle is the other important factor. The phase angles at the edge of the interference area have to be equal along the direction perpendicular to the line integral direction; unless this is so we have to use another differential component of the potential that is in two-dimensional differential interferometry.

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