

## Split-Illumination Electron Holography

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Off-axis electron holography has been used for observing microscopic distributions of magnetic fields, electrostatic potentials and strains at the nanoscale level and for aberration-corrected electron microscopy by detecting phase shifts of electron waves. An off-axis electron hologram is formed by overlapping an object wave transmitted through a sample with a reference wave passed through the reference area. The inherent problem with this method is that the distance  $D$  between the object and reference waves, or the hologram width  $W$ , is limited by the lateral coherence length  $R$  ( $= \lambda/2\beta$ , where  $\lambda$  is the electron wavelength and  $\beta$  is the half illumination angle of the electron waves) or by the brightness of the illuminating electron waves [1]. We solved this long-standing problem by developing a split-illumination electron holography that uses three sets of biprisms. Experiments were performed using a 300-kV cold field emission transmission electron microscope (TEM) (HF-3300X, Hitachi High-Technologies Co.).

In conventional electron holography [Fig. 1(a)], a hologram is formed by overlapping the object wave transmitted through the sample and the reference wave passed outside the sample and nears its edge using an electron biprism. In our split-illumination electron holography [Fig. 1(b)], we can illuminate a sample by using two highly separated and yet coherent electron waves without reducing the density of electron and form high-contrast holograms at regions far from the sample edge: the electron biprism in the illumination system is used to control the distance  $d_s$  of two waves, and double biprisms in the imaging system are used to overlap them to form a hologram. The fringe spacing  $s$  and the width  $W$  of the hologram can be independently controlled as in double-biprism electron interferometry [2]. Using split-illumination holography, a fringe contrast of 50% can be attained even if the object wave is as far as 17  $\mu\text{m}$  from the reference wave in the sample plane. Hologram formation conditions were current density  $J_{\text{obj}}$  on sample position of 1.3 A/m<sup>2</sup>, magnification at camera plane of 57,000, fringe spacing  $s$  of 30 nm and width  $W$  of 700 nm [3].

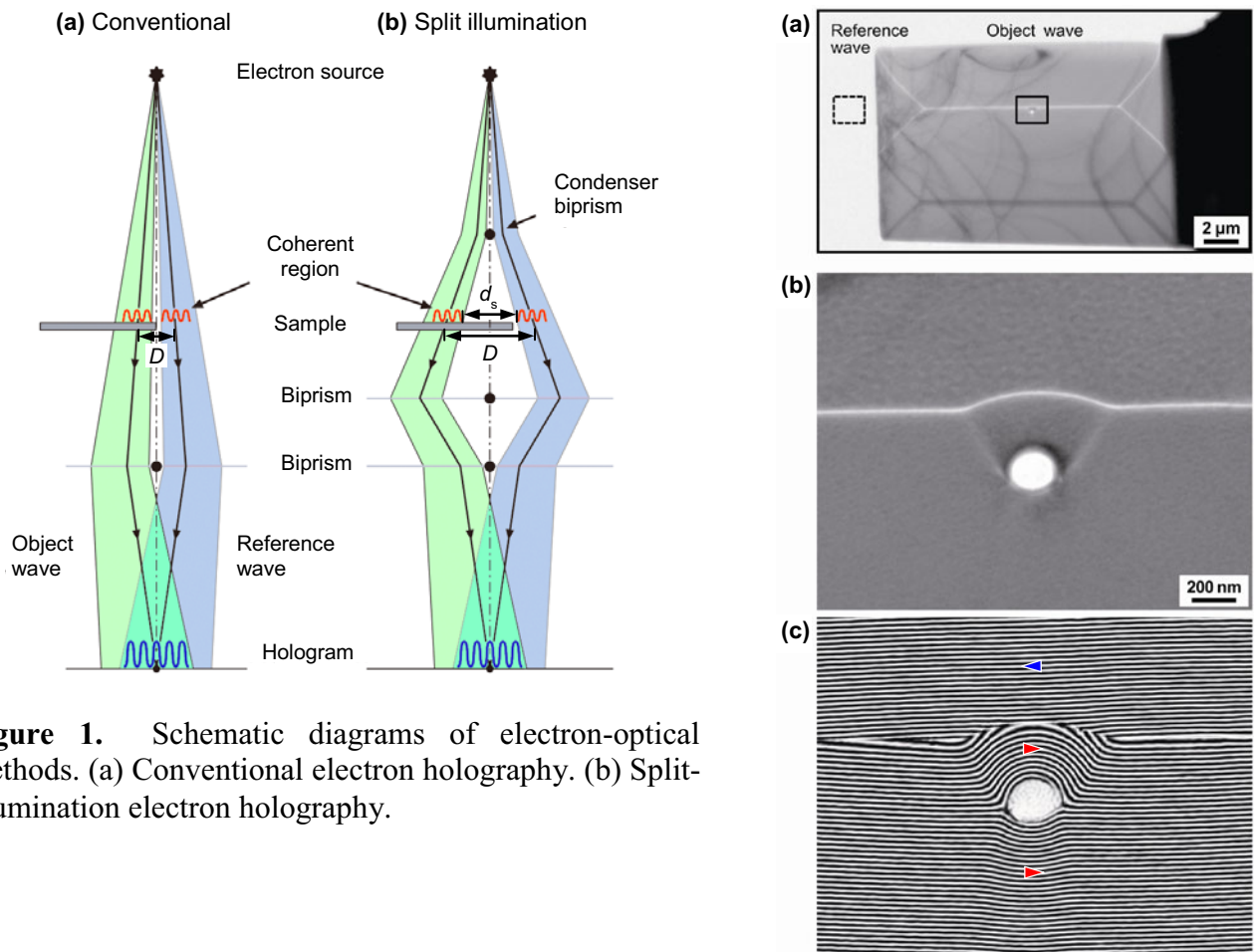
The developed split-illumination electron holography opens new possibilities for holographic observations that have been impossible with the conventional method. As one such application, we observed magnetic lines of force pinned by a submicron hole located 9  $\mu\text{m}$  from the edge of a thin electrical steel sheet [Fig. 2]. A magnified Lorentz image of the bounded area [Fig. 2(b)] shows two white domain walls and that the central domain wall is at a distance from the hole in the form of a white arc. A reconstructed phase contour map [Fig. 2(c)] shows in detail the magnetic lines of force (black lines) around the hole and their relationship to the looped magnetic lines of force at the domain walls.

This kind of holographic observation is not possible with either conventional holography or Lorentz microscopy.

In conclusion, we have developed a method long desired in electron holography for observing in a region far from the sample edge. This method can also be applied to cases in which strong magnetic or electric fields leaks out near the sample edge since far-edge non-distorted reference waves can be used.

#### References:

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 [4] The authors acknowledge to Dr. Z. Akase, Dr. Y. Murakami, Dr. H. Ichinose, Dr. K. Harada, Mr. K. Yanagisawa and Dr. Y. A. Ono for their valuable discussions. This research was supported by a grant from the Japan Society for the Promotion of Science (JSPS) through the "Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST Program)," initiated by the Council for Science and Technology Policy (CSTP).



**Figure 1.** Schematic diagrams of electron-optical methods. (a) Conventional electron holography. (b) Split-illumination electron holography.

**Figure 2.** Magnetic behavior in thin electrical steel sheet observed by split-illumination electron holography. (a) Lorentz image. (b) Magnified Lorentz micrograph of area indicated by rectangle in middle of (a). (c) Magnetic lines of force (black lines) around hole located 9  $\mu\text{m}$  from sample edge.