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Advanced split-illumination electron holography without Fresnel fringes

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ABSTRACT

Advanced split-illumination electron holography was developed by employing two biprisms in the illuminating system to split an electron wave into two coherent waves and two biprisms in the imaging system to overlap them. A focused image of an upper condenser-biprism filament was formed on the sample plane, and all other filaments were placed in its shadow. This developed system makes it possible to obtain precise reconstructed object waves without modulations due to Fresnel fringes, in addition to holograms of distant objects from reference waves.

1. Introduction

Electron holography was invented by Gabor to correct aberrations of the lenses of an electron microscope. Developments of off-axis electron holography using Möllenstedt-type electron biprisms and a field-emission electron gun [1] expanded application fields of electron holography to observing atomic arrangements [2,3], magnetic fields [4,5], electrostatic potentials [6,7], and strains [8]. An off-axis electron hologram is formed by overlapping an object wave transmitted through a sample with a reference wave passed through a well-known reference area such as a vacuum. The long-standing problem with this method, however, is that the distance between the object and reference waves (D) is limited by lateral coherence length R (which equals,$=\lambda/2\beta \propto 1/\sqrt{j}$, where λ is electron wavelength, β is the half illumination angle of the electron waves, and j is illuminating current density) of the illuminating electron waves [9]. To extend D without decreasing current density of the illuminating electron waves, split-illumination electron holography (SIEH) [10] was developed. SIEH makes it possible to acquire holograms at regions located far from the sample edge or obtain holograms with the reference waves far from the object waves to avoid distortions of the reference waves due to leakage of magnetic or electric fields from the sample.

However, phase shifts of nanoscale electrostatic and magnetic fields are small, it is necessary to improve precise phase measurements of reconstructed object waves from holograms to broaden the applications of the off-axis electron holography. Many technologies, such as phase amplification [11], using reference holograms to remove geometric distortions peculiar to the electron microscope [12], the phase-sifting method [13] and its modifications [14,15], multiple acquisitions [16], and double-biprism interferometry [17] (enabling independent control of fringe spacing (s) and width (W) of holograms without Fresnel fringes due to Fresnel diffraction at the biprism filament) have been developed. A problem concerning SIEH that remains after these developments was that phase resolution was limited by the modulations of object and reference waves by Fresnel diffraction at the biprism filament in the illuminating system. Given that remaining problem, we have devised an improved version of SIEH, which enables electron holograms to be formed without Fresnel fringes, and applied it to observe electrostatic-potential distributions in semiconductors.

2. Optical systems

In the case of conventional electron holography, the maximum distance between the object and reference waves (D_{max}) is limited

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by the lateral coherence length of the illuminating electron waves (R), and the fringe contrast of the hologram (C) decreases with increasing D (i.e., increasing width (W) of the hologram). Increasing R by decreasing β decreases the current density of the illuminating electron waves. The detectable phase shift in the phase image reconstructed from the hologram is inversely proportional to $C\sqrt{N}$, where N is the detected electron number contributing to the reconstruction of each pixel in the phase image [18]. Since increasing D while keeping reconstructed spatial resolution decreases C and N, it is quite difficult to precisely measure and observe the phase distributions at regions located far from the sample edge.

The SIEH that we previously reported [10] (hereafter, "previous SIEH") made it possible to form high-contrast holograms with large D without reducing current density by splitting an electron wave into two coherent partial waves by using a condenser biprism in the illuminating system. However, since the condenser-biprism filament was defocused at the sample plane, Fresnel fringes due to the Fresnel diffraction at the filament was not inevitable. Fresnel fringes modulated both amplitude and phase distributions of each object and reference wave. As a result, the phase images reconstructed from the holograms were modulated, i.e., an artifact [19] [see Fig. 3(b) and (d)]. A method for removing the artifact due to Fresnel fringes, by using a Gauss-type line filter during the phase-reconstruction process, has been developed [16]. However, the problem is that the phase information of the sample (object wave) is also partially removed by the filtering process. On the other hand, in regard to SIEH, Fresnel fringes due to the condenser-biprism filament can be eliminated by making the filament focused precisely on the sample plane by means of lenses between the condenser biprism and the sample. However, a single condenser biprism only tilt the illuminating electron waves without separating them. Thus, the intrinsic function of SIEH (i.e., splitting electron waves and illuminating separate areas at the sample plane) is lost.

The optical system of the proposed SIEH (hereafter, "advanced SIEH"), along with the associated parameters, is shown in Fig. 1. To keep the advantages of SIEH and acquire the hologram without Fresnel fringes ("Fresnel-fringes-free hologram" hereafter), two biprisms are installed in the illuminating system. A focused image of the filament of the upper condenser biprism is formed on the sample plane. All other biprism filaments (filaments of lower condenser biprism and two biprisms in imaging system) were placed in the shadow of the upper condenser-biprism filament. Separation distance (d_s) and tilt angle (θ) of two illuminating electron waves, given by the following equations, can be controlled by using the two biprisms in the illuminating system.

$$d_s = \frac{b_3}{a_3}(2L_3\gamma_{CL} + d_{CU}) \tag{1}$$

$$\theta = \frac{a_3}{b_3}(L_1\gamma_{CU} + L_2\gamma_{CL}) \tag{2}$$

Here, γ_{CU} and γ_{CL} are deflection angles of the electron waves at the upper and lower condenser biprisms and d_{CU} is the diameter of the filament of the upper condenser biprism. To avoid illuminations of the lower condenser-biprism filament by electron waves, the

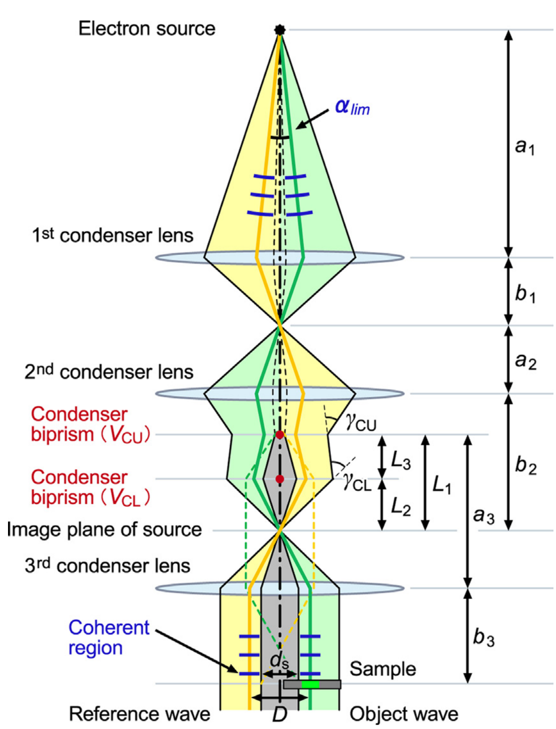

Fig. 1. Schematic diagrams of electro-optical methods. A coherent electron wave is split into two partial waves by two condenser biprisms placed in illuminating system. The upper condenser biprism filament is focused precisely on the sample plane by the third condenser lens. One partial wave (object wave) illuminates an observation area on the sample plane, and the other one (reference wave) passes through the vacuum outside the sample. Biprisms placed in imaging system (not shown) cause the waves to overlap and form a hologram. In this way, Fresnel-fringes-free holograms with a high fringe contrast can be obtained even though the object and reference waves are separated at the sample plane.

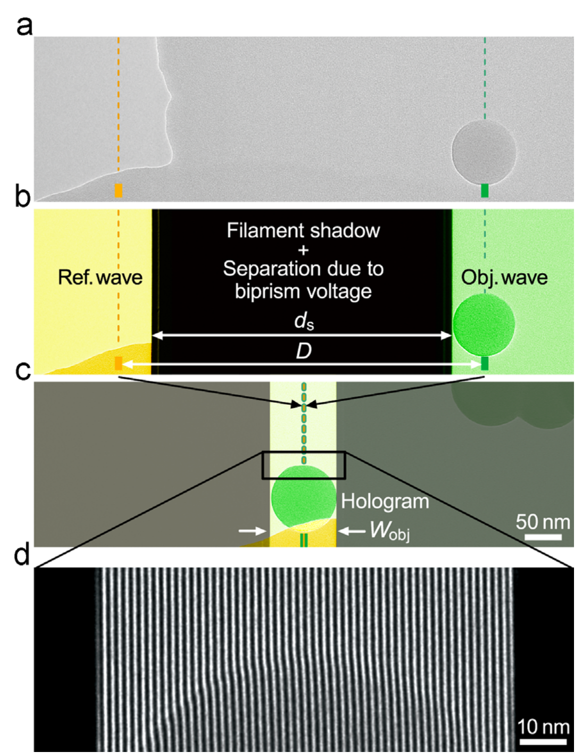

Fig. 2. Formation of Fresnel-fringes-free hologram by advanced split-illumination electron holography. (a) TEM image of a latex particle (as an object) on the carbon film. (b) First, all biprisms are inserted, and $V_{CU} = -50$ V is applied to make a shadow of upper condenser-biprism filament. Coherent electron waves are split by applying $V_{CL} = 150$ V. (c) Waves are overlapping to form a hologram by applying $V_L = 150$ V. (d) Magnified holograms indicated by a rectangle in (c) are obtained by applying $V_U = -20$ V. Fresnel-fringes-free hologram with D of 500 nm between object and reference waves were obtained. Hologram formation conditions: current density on sample plane (J_{obj}) of 3.7×10^2 A/m^2, and width (W_{obj}) of 90 nm. Fringe contrast was 29%. In contrast, the fringe contrast without split-illumination was less than 2.5% under this experimental condition.