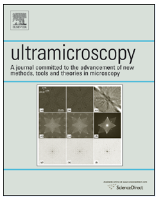
Ultramicroscopy 147 (2014) 33–43

Contents lists available at ScienceDirect

Ultramicroscopy

journal homepage: www.elsevier.com/locate/ultramic



Advanced double-biprism holography with atomic resolution

Florian Genz [a,*], Tore Niermann [a], Bart Buijsse [b], Bert Freitag [b], Michael Lehmann [a]

[a] *Technische Universität Berlin, Institut für Optik und Atomare Physik, Straße des 17. Juni, 10623 Berlin, Germany*
[b] *FEI Company, Achtseweg Noord 5, 5651 GG Eindhoven, The Netherlands*

ARTICLE INFO

Article history:
Received 11 April 2014
Received in revised form
5 June 2014
Accepted 8 June 2014
Available online 23 June 2014

Keywords:
Electron holography
Optimum biprism position
Double biprism
HRTEM

ABSTRACT

The optimum biprism position as suggested by Lichte (Ultramicroscopy 64 (1996) 79 [10]) was implemented into a state-of-the-art transmission electron microscope. For a setup optimized for atomic resolution holograms with a width of 30 nm and a fringe spacing of 30 pm, we investigated the practical improvements on hologram quality. The setup is additionally supplemented by a second biprism as suggested by Harada et al. (Applied Physics Letters 84 (2004) 3229 [12]). In order to estimate the possibilities and limitations of the double biprism setup, geometric optics arguments lead to calculation of the exploitable shadow width, necessary for strong reduction of biprism-induced artefacts. Additionally, we used the double biprism setup to estimate the biprism vibration, yielding the most stable imaging conditions with lowest overall fringe contrast damping. Electron holograms of GaN demonstrate the good match between experiment and simulation, also as a consequence of the improved stability.

1. Introduction

Electron holography takes a special place among transmission electron microscope investigation methods. By giving access to the phase of the image wave, it enables several applications, e.g., measurement of magnetic domains [1] and mean inner potentials [2], or mapping of potential distributions [3] and, in dark-field mode, strain fields [4]. As in every scientific investigation method, electron holography undergoes continuous improvements to overcome old obstacles from the experimental setup [5]. Accordingly, the Cs-corrector [6] was integrated beneficially into the measurement process [7], the gap between high resolution and Lorentz mode was closed [8], and a new high-brightness Schottky field emitter was introduced, which is most beneficial for high resolution holography [9].

Regarding mechanical and electrical instabilities of the biprism, geometric optics considerations led to the derivation of the optimum biprism position [10]. In the optimum biprism position, the influence of these instabilities is reduced by minimizing the deflection angle of the biprism. This improves the interference fringe contrast, which is directly correlated with the signal-to-noise ratio of the reconstructed phase signal [11].

Other restrictions are the Fresnel fringes artefact, or the mutual dependence of hologram width and fringe spacing on the filament voltage. These restrictions can be reduced strongly by using a double biprism setup [12].

In the following, the two approaches, the biprism position optimization and the double biprism setup, and their new degrees of freedom are elaborated at first, as well as their limitations, e.g., the influence of the shadow width on the vignetting effect and the fringe contrast damping by biprism vibrations. Afterwards, they were applied to a state-of-the-art transmission electron microscope that is specially designed for electron holography, especially for atomic resolution holography. The intended parameters are a hologram width of 30 nm and a fringe spacing of 30 pm because the reconstruction of off-axis electron holograms requires a fringe spacing at least two to three times smaller than the information limit, which is about 80 pm in our microscope.

The focus of this work is atomic resolution off-axis electron holography. Nevertheless, most aspects are applicable in medium resolution holography as well.

2. Theory

2.1. Conventional single biprism setup

In the off-axis electron holography, the phase of the image wave is retained in an interference of the image wave with an empty reference wave. For this process a Möllenstedt biprism is used, which divides the electron beam into two partial waves [13]. The partial waves are tilted towards each other by applying a

---

[*] Corresponding author. Tel.: +49 30 314 29077.
E-mail address: florian.genz@physik.tu-berlin.de (F. Genz).

http://dx.doi.org/10.1016/j.ultramic.2014.06.002
0304-3991/© 2014 Elsevier B.V. All rights reserved.

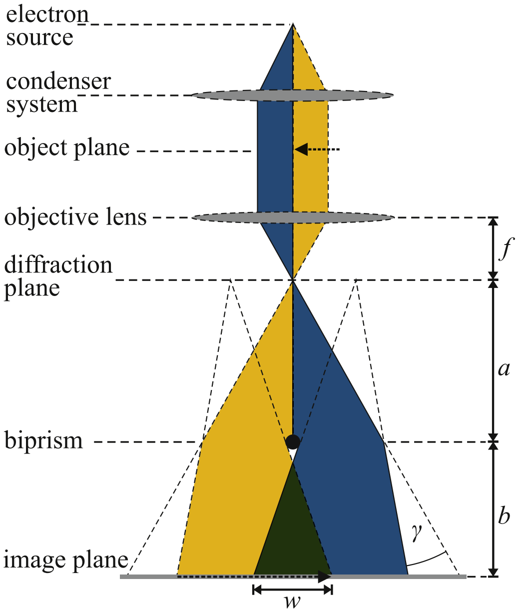


Fig. 1. Schematic sketch of beam paths in conventional off-axis electron holography using a single biprism. For the sake of simplicity, the Cs-corrector is not shown.

positive voltage U_f to the biprism filament (Fig. 1). This process is practically without any geometric aberrations [14].

The key properties of the hologram are its width w and fringe spacing s. The hologram width w, related to the object plane, is given by the biprism shear w_{01} and the biprism shadow $w_{s\ 1}$:

$$w = w_{01} - w_{s1} = \frac{1}{M_{ol}} \cdot \left(2\gamma b - 2r_f \frac{a+b}{a}\right), \tag{1}$$

where r_f is the radius of the biprism filament and γ its deflection angle [15,16]. The magnification of the objective lens (or in image Cs-corrected instruments, the total magnification of the objective lens and the Cs-corrector) is M_{ol}, a is the distance between the diffraction plane of the objective lens and the biprism plane, and b is the distance between the biprism plane and the first image plane (Fig. 1). The deflection angle γ is the product of the biprism constant γ_0 and the applied voltage U_f [17]:

$$\gamma = \gamma_0 \cdot U_f. \tag{2}$$

The fringe spacing s, related to the object plane, is given by

$$s = \frac{1}{M_{ol}} \cdot \frac{\lambda(a+b)}{2\gamma a}, \tag{3}$$

where λ is the electron wavelength [15,16].

2.2. Biprism induced artefacts

Since the biprism is not located in a principal plane, e.g., in the first image plane, it generates the Fresnel fringes at coherent illumination, which are still visible in the final hologram. Additionally, it may block some parts of deflected beams, known as vignetting effect [18], as sketched in Fig. 2. Consequently, the undisturbed field of view of the hologram is decreased. Depending on the setup parameters and the desired spatial resolution, both artefacts may strongly hamper the interpretability of acquired holograms [18].

2.3. Double biprism setup

In the double biprism setup (Fig. 3), the first biprism is placed in the first image plane, where it is sharply imaged by the subsequent lens and hence does not produce the Fresnel fringes in the hologram [12]. The second biprism is located in the geometric shadow of the first biprism, where it does not generate the Fresnel fringes. Both biprisms are separated by an additional lens (called extra lens or XL in the following), which grants, in addition to the biprism voltages of the two biprisms, an additional degree of freedom. This special electron-optical setup is highly flexible and offers different ways of hologram acquisition, as described in [19].

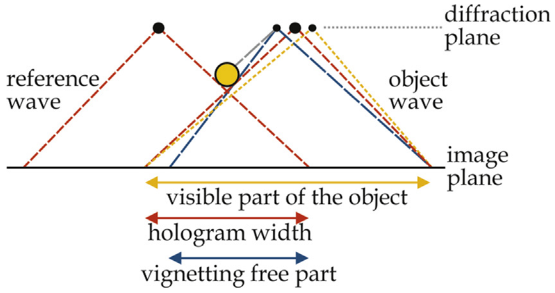


Fig. 2. Schematic sketch of vignetting caused by the biprism. Parts of the crystallographic reflections may be blocked by the biprism filament.

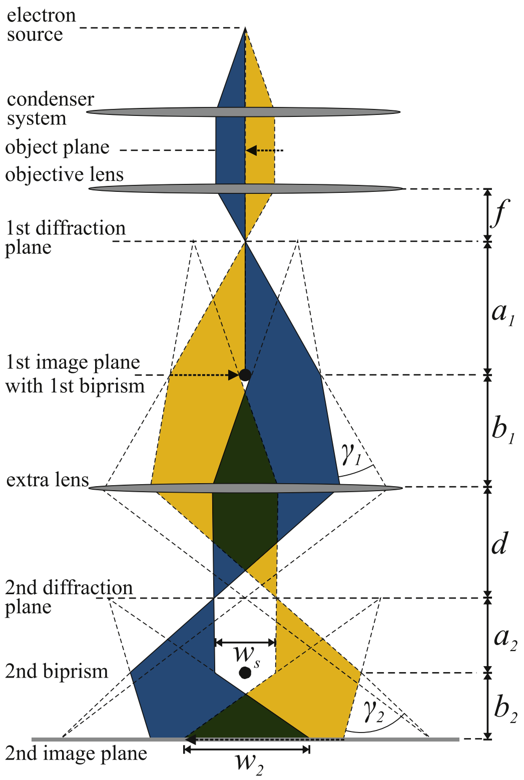


Fig. 3. Schematic sketch of components and beam paths in double biprism electron holography. Green region in the middle marks the overlap of both partial waves. The Cs-corrector, which is located between objective lens and first biprism, is not drawn for the sake of simplicity. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this paper.)

Related to the object plane, the hologram width w_2 is given by the shear of the second biprism w_{02} and the shadow of the first biprism $w_{s\ 2}$:

$$w_2 = w_{02} - w_{s2} = \frac{1}{M_{ol}M_{xl}} \cdot 2\gamma_2 b_2 - \frac{1}{M_{ol}} \cdot 2r_{f1}. \tag{4}$$