doi:10.1017/S1431927617003646
Microsc. Microanal. 23 (Suppl 1), 2017

Non-Diffractive Electron Bessel Beams for Scanning Electron Microscopy in Transmission Mode Using Direct Phase Masks

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Electron-beam shaping has drawn significant attention since the generation of an electron vortex beam has been successfully demonstrated [1,2]. Utilizing structured thin films or apertures which influence the amplitude and/or phase of an illuminating electron wave allows the production of specific types of electron beams. In this research project we focus on fabrication and application of non-diffractive electron beams [3,4] using direct phase masks (PMs) to create single beams with high intensity. Non-diffractive electron beams have a constant beam profile upon propagation possibly allowing focused imaging of thick samples in scanning modes in electron microscopy (EM) [5]. Additionally, non-diffractive beams theoretically have the smallest beam diameter and could thus even improve the resolution in EM. To our knowledge, electron-beam shaping has up to now only been applied in transmission (T)EM although it can be beneficial in scanning (S)EM, especially in combination with channelling effects. We present our recent progress in the fabrication of direct PMs for non-diffractive electron beams and their application.

Fabrication of the PMs is performed by electron-beam evaporation of a Pt protective layer on a Si_3N_4-membrane and subsequent structuring using a FEI Dual-beam Strata 400S focused ion beam system. To ensure reasonable conductivity under electron-beam illumination, the backside of the PM is coated with a thin layer of amorphous carbon. SEM, TEM and atomic force microscopy (AFM) techniques are used to characterize the PMs. The evolution of the propagating electron wave after transmission through the PM is analysed in the low-magnification mode of a FEI Titan³ 80-300 with a script written for Digital Micrograph. In parallel to the experimental observation of the non-diffractive beam by TEM, simulations are performed using Matlab.

The analysis of a PM producing a single non-diffractive beam with high intensity is displayed in Figure 1. The SEM image of the tilted PM shows the protective Pt coating with a round aperture (Figure 1a). The structured thickness profile within the Si_3N_4-membrane consists of rings with a depth of approximately 25 nm as revealed by the AFM image. The Pt protection ensures that illuminating electrons can only propagate through the PM leading to the contrast observed in a focused TEM image of the PM (Figure 1b). Shortly after transmission through the PM, the electron wave evolves in a Bessel function with a central maximum of high intensity and surrounding concentric rings (Figure 1c). This shape is conserved upon further propagation revealing the non-diffractive property of the electron beam (Figure 1b-e).

A detailed investigation of the TEM images in Figure 1b-e indicates a decrease of the entire electron beam in size which can be attributed to the presence of a focusing lens. Depending on the electron wavelength λ, the periodicity of structured rings k_0 and the diameter of the aperture D, the non-diffractive property is maintained in field-free space up to a specific propagation length, which is $L = D/(2\lambda k_0) = 1$ m for the used PM. The intensity of the central maximum (I_{CM}) is increasing upon propagation and reaches its maximum at L [3,4]. Figure 2a shows the evolution of I_{CM} determined from a series of TEM images in dependence of the propagation length. I_{CM} is increasing up to a distance of only 135 mm before rapidly decreasing again. The final strong increase is caused by the focusing lens and corresponds to the back focal plane of the lens. The experimental findings are confirmed by simulation of the evolution of the electron wave function using Fresnel propagation and consideration of the actual structure of the experimental PM and a focusing lens resulting in a qualitatively similar behaviour of I_{CM} (Figure 2b).

An implementation of a PM in the condenser lens system of an electron microscope allows the generation of non-diffractive electron beams which can be used for imaging. Control over the beam shape is not only given by the geometry of the mask but also by the excitation of the condenser lenses [6].

References:

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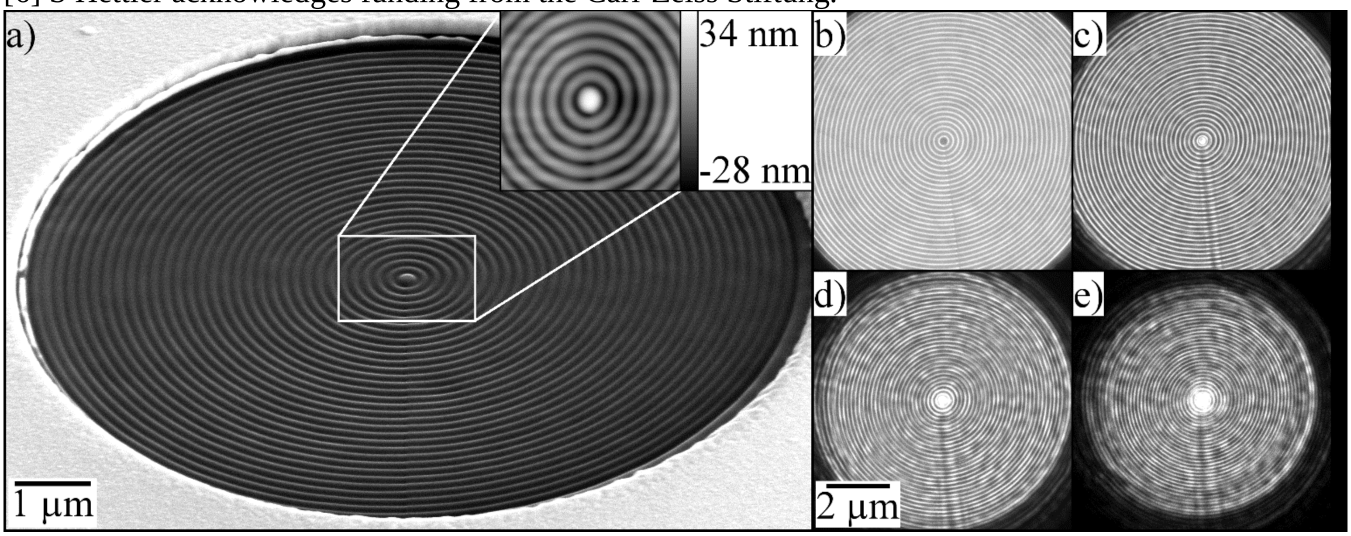

Figure 1. Experimental analysis of a PM for production of a single non-diffractive electron beam with high intensity. (a) The SEM image shows the surrounding Pt protective layer (bright) and the thickness profile within the Si_3N_4 membrane which is revealed in the AFM image (inset). (b-e) TEM images of the electron wave after transmission through the PM and a following propagation of (b) 0 mm, (c) 21 mm, (d) 42 mm and (e) 64 mm.

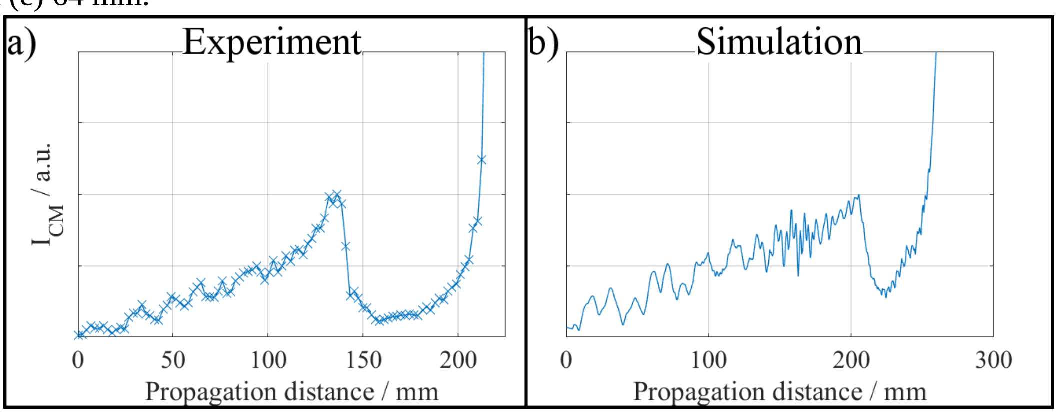

Figure 2. Evolution of I_{CM} in dependence of the propagation distance (a) determined from experimental images and (b) simulated I_{CM} considering the actual structure of the PM (Figure 1a) and a focusing lens.