Ultramicroscopy 163 (2016) 69–74

Contents lists available at ScienceDirect

Ultramicroscopy

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

Prospects for electron beam aberration correction using sculpted phase masks

Roy Shiloh [*,1], Roei Remez [1], Ady Arie

School of Electrical Engineering, Fleischman Faculty of Engineering, Tel Aviv University, Tel Aviv, Israel

ARTICLE INFO

Article history:
Received 21 October 2015
Received in revised form
3 January 2016
Accepted 18 February 2016
Available online 20 February 2016

Keywords:
Phase-masks
Thin film membranes
Phase-plates
Aberration correction
Electron column

ABSTRACT

Technological advances in fabrication methods allowed the microscopy community to take incremental steps towards perfecting the electron microscope, and magnetic lens design in particular. Still, state of the art aberration-corrected microscopes are yet 20–30 times shy of the theoretical electron diffraction limit. Moreover, these microscopes consume significant physical space and are very expensive. Here, we show how a thin, sculpted membrane is used as a phase-mask to induce specific aberrations into an electron beam probe in a standard high resolution TEM. In particular, we experimentally demonstrate beam splitting, two-fold astigmatism, three-fold astigmatism, and spherical aberration.

© 2016 Elsevier B.V. All rights reserved.

1. Introduction

The standard method nowadays to shape electron beams is based on applying magnetic or electric forces to the electrons, however, it is also possible to use phase masks for shaping the phase front of the electron beam. The idea of using material foils of constant thickness to change the phase of the electron beam was proposed by Boersch in 1947 [1] as an implementation of Zernike's phase contrast method. In 1975, Willasch [2] and Muller [3] fabricated profiled phase-plates with alternating thicknesses, with the ultimate goal of imprinting the aberrated beam with spherical aberration of the equal magnitude but opposite sign, thereby cancelling it. The thickness profile was achieved using contamination build-up. In 1998 Ito et. al.[4] created pixelated Fresnel lenses by drilling holes in $AlF3$ with an electron beam. While the holes are of very small dimensions, they are unfortunately separated, which contributes to the difficulty of achieving a smooth phase front. In all of the above mentioned examples, the nanofabrication technology we have today has not yet matured. This situation has changed now with the emergence of new technologies and techniques – e.g. focused ion beam milling and deposition, electron beam lithography, as well as ultrathin membranes of materials such as silicon nitride (SiN), yielding a variety of opportunities for electron beam shaping [5–10] and contrast enhancement [11–13]. In this Letter, we show several examples of electron probe shaping using nanoscale phase-masks, namely: half-beam tilt, two-fold astigmatism, three-fold astigmatism, and spherical aberration. In these examples, we illustrate and measure new and wide-ranging capabilities for correcting aberrations in electron columns with patterned phase masks. We achieve this by inducing aberrations to a diffraction limited electron beam, and argue that correction of such is equivalent.

In different systems employing an electron-beam column, such as scanning electron microscopes (SEM), scanning-TEMs (STEM), and e-beam lithography machines, the electron probe scans across the target sample in a raster manner, synchronizing the reading of backscattered or secondary-emitted electrons to form an image or inscribe a pattern for further processing. It is therefore important that the electron probe size be as ideal, or as small as possible, or that the probe is otherwise arbitrarily shaped, as could be required by certain applications; this would also be true for many other applications that use an electron probe, notably the generation of sub-diffraction electron probes [14]. With today's technological achievements in lens design, the dominant probe aberrations in a generic column would be the result of a combination of the probe-forming optics: the gun, condenser, and objective lenses. Avoiding the implausible alteration of the entire, commercial optical design, a probe wavefront shaper would be best placed in the condenser aperture, where the beam dimensions are demagnified. This location enjoys a highly important advantage: the beam diameter is much larger, typically ~60 μm, compared to ~300 pm in the focal plane, yielding a current density on the mask which is lower by

* Corresponding author.
E-mail address: royshilo@post.tau.ac.il (R. Shiloh).
[1] These authors contributed equally to this work.

http://dx.doi.org/10.1016/j.ultramic.2016.02.002
0304-3991/© 2016 Elsevier B.V. All rights reserved.

more than 10 orders of magnitude. Thus, ill effects such as charging, radiation damage, and contamination are much diminished and more easily dealt with compared to the case of contrast-enhancing phase plates [15], which are mounted in the diffraction plane of the objective lens.

Once the ability to nearly-arbitrarily control the phase front of the electron wave has been established [8], it is possible to compensate for electron aberrations: one can simply design the phase transparency, or a patterned thin membrane, with the inverse of the expected wavefront aberration. We employ the same idea in our designs, where a 200 keV electron with 2.51 pm wavelength accumulates a 2π phase shift in a SiN membrane with thickness of approximately $t_{2\pi}$=84 nm thick. It is imperative to note that other authors [16,17] deduced a different thickness for SiN than ours, however, the total phase shift is additionally a function of other factors such as the electron acceleration voltage, Gallium implantation dependent on our FIB parameters, and the membrane fabrication process, which differs from vendor to vendor [18]. Our 100 nm SiN membranes were purchased from SPI Supplies.

We define the amount of aberrations using the largest optical path difference, or "peak-to-valley", of the aberrated wavefront from an ideal spherical wavefront, measured in 2π phase cycles multiplied by the wavelength λ [19]. For aberrations larger than 1λ, in order to avoid overly thick membranes, the transparencies are designed in either binary or modulo-2π fashion, such as in the case of diffractive elements in light optics [20].

2. Aberration-inducing phase masks

As introductory, quantitative examples, we will discuss phase-masks that induce a half-beam tilt, two-fold astigmatism, three-fold astigmatism, and spherical aberration, as depicted in Fig. 1(a), Fig. 2(a), Fig. 3(a), and Fig. 4(a), respectively. Cross-sections of the image intensity, taken at image focus along the dashed line, qualitatively imply the topographic profile of the phase-mask, assuming a linear relation between the two; these are correspondingly presented in the insets of each figure. The phase-masks are placed in the sample holder and we use low magnification mode, where the objective lens is essentially off, imaging the back-focal plane of the diffraction lens to the screen through an objective aperture of 10 μm diameter (or 30 μm for the spherical aberration mask). The same method could be demonstrated in our microscope with the objective lens rather than the diffraction lens, but owing to its much shorter focal length (1.7 mm vs 100 mm for the diffraction lens), the beam size would be already too small when imaged to the camera.

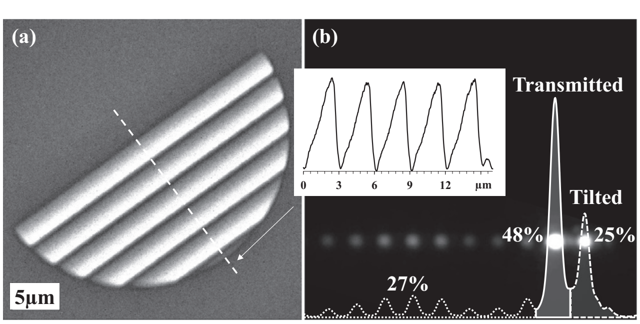

Fig. 1. Half-beam tilt: (a) fabricated phase-mask, dashed line marking extents of the intensity cross-section in the inset. (b) Measured diffraction image, with the relative intensity distribution marked for the transmitted beam (48%, thick line), tilted beam (25%, dashed line), and higher diffraction orders (27%, dotted line). Contrast and brightness altered for visibility.

2.1. Half-beam tilt

In the half-beam tilt mask, Fig. 1, the circular illumination encompasses both the modulated and unmodulated semi-circles of the phase-mask. As the modulated half is a blazed grating [16,17], well known in diffractive light optics, we expect half of the intensity to propagate unperturbed (transmitted, or zero order) and half to tilt to the first order of the grating, neglecting intensity lost due to high-angle scattering. The angle of the tilted beam is predesigned according to the grating period. Indeed, the measurement in Fig.1(b) shows the expected on axis beam and another significant tilted beam located to its right (having 48% and 25%, respectively, of the total transmitted intensity as measured here). The ill effects of fabrication faults manifest themselves as additional, low-intensity diffraction orders, and uneven distribution of

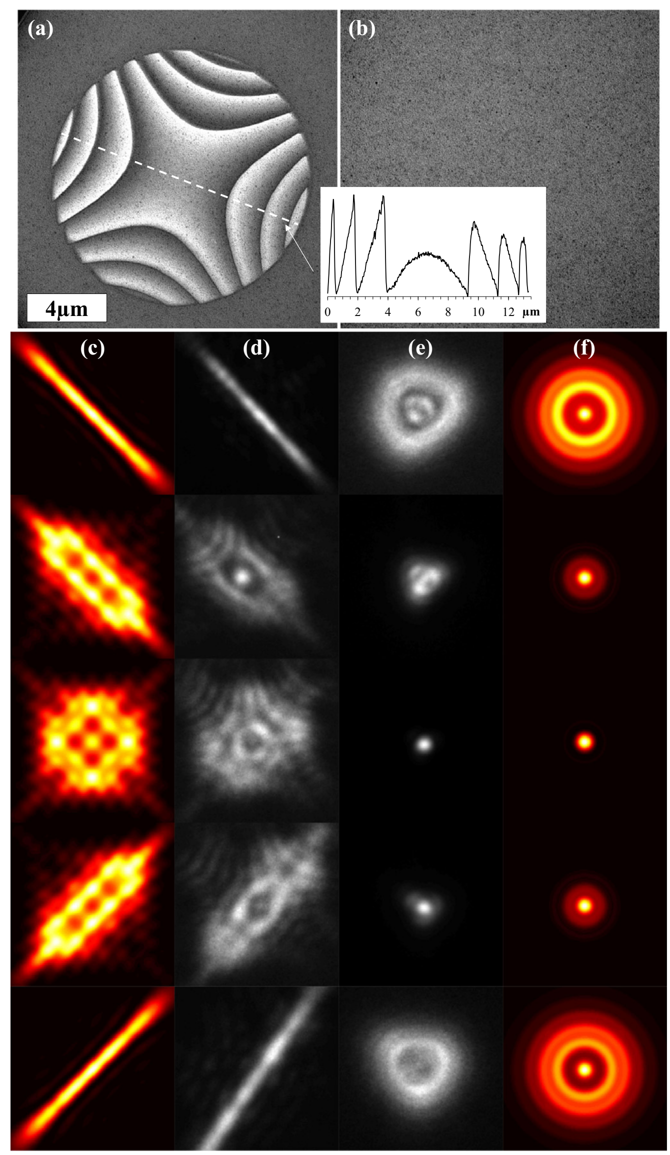

Fig. 2. Two-fold astigmatism: (a) fabricated phase-mask, dashed line marking extents of the intensity cross-section in the inset, where the slight decline observed in the inset is assumed to be due to a nonlinear response of the CCD sensor or lack of uniformity of the beam intensity profile in this particular measurement. (b) Unmodulated area on the membrane, measured for reference. Astigmatic focal series: comparison of (c) simulation and (d) experiment, and the corresponding reference (f) simulation and (e) experiment. Contrast and brightness altered for visibility.

Download English Version:

https://daneshyari.com/en/article/8037930

Download Persian Version:

https://daneshyari.com/article/8037930

Daneshyari.com