Tabletop Nanometer Extreme Ultraviolet Imaging in an Extended Reflection Mode Using Coherent Fresnel Ptychography: supplementary material

MATTHEW D. SEABERG^{1,*}, BOSHENG ZHANG¹, DENNIS F. GARDNER¹, ELISABETH R. SHANBLATT¹, MARGARET M. MURNANE¹, HENRY C. KAPTEYN¹, AND DANIEL E. ADAMS¹

¹JILA, University of Colorado at Boulder, Boulder, CO 80309, USA

*Corresponding author: matthew.seaberg@colorado.edu

Published 22 July 2014

This document provides supplementary information to “Tabletop Nanometer Extreme Ultraviolet Imaging in an Extended Reflection Mode Using Coherent Fresnel Ptychography,” <http://dx.doi.org/10.1364/optica.1.000039>. Here we perform consistency checks to ensure that the reconstructed illumination was retrieved properly. Additionally, we make a detailed comparison between the amplitude and phase of the ptychographic reconstruction and images obtained from scanning electron and atomic force microscopes. Finally, we provide information pertaining to image reconstruction, sample fabrication, and oxide layer measurement methods. © 2014 Optical Society of America

OCIS codes: (180.0180) Microscopy; (180.7460) X-ray microscopy; (190.2620) Harmonic generation and mixing; (120.5050) Phase measurement.

<http://dx.doi.org/10.1364/optica.1.000039.s001>

A. HIGH HARMONIC BEAM CHARACTERIZATION THROUGH PTYCHOGRAPHY

To ensure that our recovery algorithm as discussed in the main text was correctly retrieving the probe illumination, we first characterized the extreme ultraviolet (EUV), high harmonic generation (HHG) beam by scanning a 5 μm diameter pinhole across the beam near its focus and reconstructed the illumination using ptychography. In this case, the pinhole can be thought of as the probe, while the beam is an effective object. The scan consisted of a 6×6 grid with 1 μm step size between adjacent scan positions. The reconstructed beam is shown in Fig. S1a.

The reconstructed beam was propagated to the sample position (200 μm upstream of the pinhole probe location) and calculated on the tilted plane (at 45°) using tilted plane correction, shown in Fig. S1b. Immediately after this ptychography scan, the pinhole probe was removed and the sample was translated such that the beam illuminated one of the star patterns on the sample (with reconstruction shown in Fig. 2d). We performed a 3×3 ptychographic scan across the star feature, with 2.5 μm step size. In this case, a probe starting guess consisting of a

Gaussian amplitude profile with random phase sufficed to consistently retrieve the probe amplitude shown in Fig. S1c. As can be seen by comparison of Figs. S1b and c, the two beam characterization methods show very good agreement between both the phase and the amplitude. It should be noted that the HHG beam drifted slightly inside the adjustable aperture during the course of the two scans, resulting in slightly different beam structure during the two measurements.

As a further consistency check, the probe reconstruction discussed in the main text (shown in Fig. 2c) was propagated to the detector, and the tilted plane correction was undone in order to examine the result in the real coordinates of the detector. The result of these steps is shown in Fig. S2a. A comparison was made with a direct measurement of the unscattered beam by translating the sample to a featureless region of the silicon substrate, shown in Fig. S2b. As can be seen in Figs. S2a and b, while it is evident that, as in the above sample plane comparison, some beam drift occurred during the course of the ptychographic scan, the reconstructed probe is entirely consistent with the high harmonic beam used to illuminate the sample.

Fig. S1. A comparison of separate reconstructions of the HHG illumination beam, using the beam as the object in one case and as the probe in the second case. (a) Reconstruction of the HHG beam near the focus using a 5 μm diameter pinhole probe. The main image displays the amplitude and the inset displays the phase. The scale bar has width 2 μm . (b) The result of propagating the reconstructed beam from (a) to the tilted sample plane. Again, the main image shows the amplitude and the inset shows the phase. The scale bar has width 5 μm . (c) The amplitude (main image) and phase (inset) of the reconstructed probe based on a 3×3 ptychographic scan across the one of the features on the titanium sample discussed in the text. The scale bar is shared with (b). Note that the beam amplitudes in (b) and (c) are displayed in the tilted sample coordinates, resulting in elongation in the horizontal direction.

Fig. S2. Comparison between the illumination reconstructed as a ptychographic probe and propagated to the detector, and the unscattered illumination measured directly on the detector (raw data). (a) The probe reconstruction from Fig. 2c in the main text, propagated to the detector plane. (b) The HHG beam measured directly on the detector by translating the sample to a featureless region of the silicon substrate. The scale bar in (a) has width 1 mm and is shared by (a) and (b).

B. COMPARISON BETWEEN CDI RECONSTRUCTION AND SEM AND AFM IMAGES

As mentioned in the main text, there are a number of defects visible in the sample image reconstructed through ptychographic coherent diffractive imaging (CDI) which are also visible in scanning electron microscope (SEM) and atomic force microscope (AFM) images. A visual comparison between the three techniques is shown in Fig. S3. Of the 7 defects pointed out in the figure, only defects 1-5 are visible in all of the images. The 6th and 7th defects are only visible in the CDI phase image and the AFM image. This is a demonstration of the fact that CDI has both amplitude contrast (analogous to SEM) and phase/height contrast (analogous to AFM).

C. METHODS

A. Image reconstruction

The process for obtaining the reconstruction shown in Fig. 2d in the main text was as follows:

1. Tilted plane correction was applied to each of the 90 diffraction patterns in the full dataset.
2. The standard ePIE algorithm [1] was applied to the corrected data, with subpixel scan position precision handled as in Maiden *et al.* [2]. A starting guess for the probe was calculated using knowledge of the sample-to-focus distance (300 μm). The object starting guess was set to unity and the probe guess was normalized to contain the same energy as the average diffraction pattern in the dataset. The algorithm was allowed to update the probe guess in parallel with the object guess at each sub-iteration. The algorithm was run in this way for 20 full ptychographic iterations, at which point the probe guess had made much more progress towards convergence than the object guess. The object guess was reinitialized to unity, and the algorithm was restarted using the new probe guess, and allowed to run for 100 iterations, long enough for both the object and probe to converge to stable solutions.
3. The object guess was re-initialized as described in step 2, and the probe guess was set to that found at the end of step 2. The subpixel position correction method [3] was applied to the ePIE, and the overlap constraint was applied with subpixel shifts of the probe [2]. The position correction feedback parameter β was started at a value of 50, and automated as in Zhang *et al.* [3]. The probe guess was not allowed to update during this step. Again, the algorithm was run for 100 iterations, until the position corrections converged to < 0.1 pixel.
4. Finally, using the probe found in step 2 and the corrected scan positions found in step 3, and with the object guess reinitialized to unity, the algorithm was run for 200 iterations to achieve the final reconstruction.

Each full iteration (cycling through all 90 diffraction patterns) took approximately 30 seconds on a personal computer, leading to a total reconstruction time of 3.5 hours.

B. Sample fabrication

The sample used in the experiment was fabricated on a super-polished silicon wafer. The wafer was rinsed with acetone, isopropanol, and methanol, and baked on a hotplate for 20 minutes

at 250° C. It was then spin-coated with Microchem 2% PMMA in anisole, molecular weight 950 at 4000 r.p.m. for 45 seconds. Afterwards it was baked at 180° C for 90 seconds. Electron beam lithography was performed using a FEI Nova NanoSEM 640, using Nanometer Pattern Generation System (NPGS) software and patterns. The resist was then developed by immersion in a 1:3 solution of methyl-isobutyl-ketone:isopropanol for 30 seconds. Approximately 30 nm of titanium was evaporated onto the surface using a CVC SC3000 3-boat thermal evaporator. The lift-off step was accomplished in acetone using a sonicator.

C. Oxide layer measurement

The thickness of the oxide layer on the Si wafer used for sample fabrication was determined through ellipsometry (Gaertner Scientific L117F300). The measurements were made at 70° angle of incidence using a He-Ne laser at 632.8 nm. The ellipsometric angles ψ and Δ were determined to be 10.20(4)° and 171.00(7)°, respectively. The angles are defined as

$$\frac{r_p}{r_s} = \tan \psi e^{-i\Delta} \quad (1)$$

where r_p and r_s are the complex reflectivity coefficients for p - and s -polarized light, respectively. The thickness of the oxide layer was calculated by numerically solving the argument of Eq. (1), assuming an index of refraction for the oxide layer of 1.474(3) and an index of refraction for the silicon substrate of 3.89(2) + i 0.011(9) at 632.8 nm wavelength. The result, as stated in the main text, was an oxide layer thickness of 3.0(1) nm.

REFERENCES

1. A. M. Maiden and J. M. Rodenburg, "An improved ptychographical phase retrieval algorithm for diffractive imaging." *Ultramicroscopy* **109**, 1256–62 (2009).
2. A. M. Maiden, M. J. Humphry, F. Zhang, and J. M. Rodenburg, "Superresolution imaging via ptychography." *J. Opt. Soc. Am. A. Opt. Image Sci. Vis.* **28**, 604–12 (2011).
3. F. Zhang, I. Peterson, J. Vila-comamala, A. Diaz, R. Bean, B. Chen, A. Menzel, I. K. Robinson, and J. M. Rodenburg, "Translation position determination in ptychographic coherent diffraction imaging," *Opt. Express* **21**, 13592–13606 (2013).

Fig. S3. A visual comparison between the reconstructed CDI amplitude and phase with images obtained using SEM and AFM. (a) Reconstructed CDI amplitude image of the sample. (b) Phase of the reconstructed image. (c) SEM image of the sample. (d) AFM image of the sample. In the above images, 7 defects have been pointed out (located above and to the right of each number). Defects 1-5 are visible in all of the images, whereas defects 6 and 7 are only visible in the reconstructed phase and in the AFM image. The circled defect in (c) and (d) was a result of contamination after the CDI measurements were taken.