

# EUV grazing-incidence lensless imaging wafer metrology

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## ABSTRACT

Non-destructive metrology for photomasks and wafers has always been an important requirement for semiconductor lithography, and with the advent of EUVL, enabling further shrinkage of semiconductor devices, the challenges in this field have increased significantly. Coherent diffraction imaging (CDI) is a promising alternative to standard imaging for EUV photomask actinic inspection. EUV light can also be used for wafer inspection to benefit from the resolution improvement allowed by its short wavelength. In order to perform lensless imaging for patterned wafers, however, we need to probe the sample surface at grazing incidence to ensure a sufficiently high reflectance. The EUV reflective grazing incidence nanoscope (REGINE) at the Swiss Light Source was developed to perform grazing incidence lensless imaging for patterned wafers. REGINE is a tool that combines CDI, scatterometry and reflectometry in the photon energy range between 80 to 200 eV, and at the grazing incidence angle of 1 to 28 degrees. In this work, we will present the latest characterization of our system, and preliminary results.

**Keywords:** EUV, lensless imaging, wafer metrology

## 1. INTRODUCTION

At the current technology node, semiconductor devices become very complex in shape and material composition, and at the same time, the size is being pushed towards the limit of fabrication techniques. In order to have better quality control and monitor the fabrication process, advanced metrology techniques are required. The wafer metrology ecosystem includes a large range of techniques that cover a wide range of resolutions on both lateral and vertical directions and focus on different metrics. However, each method has its own limits. Optical microscopes are fast and allow a large surface section to be investigated quickly, but their resolution is limited, therefore, they are usually used when high lateral resolution is not demanded.<sup>1</sup> The scanning electron microscope (SEM) is another versatile tool with large dynamic range of magnifications.<sup>2</sup> It is capable to measure surface and subsurface features, but with the potential of sample damage. The atomic force microscope (AFM) provides high resolution, non-destructive measurement for surface roughness and topography, however, it is rather slow and limited to small areas.<sup>3</sup> Other non-destructive techniques, such as scatterometry and reflectometry, are powerful tools for the measurement of certain parameters, but they are only suitable for periodic structures and thin films, respectively. The choice of techniques is highly dependent on the measuring situation. In order to provide an comprehensive metrology platform, and to explore the potential of coherent diffraction imaging (CDI) for wafer metrology, we are developing a prototype platform, REGINE, the reflective grazing incidence nanoscope for EUV.<sup>4</sup>

## 2. REGINE OVERVIEW

REGINE is installed at the XIL beamline of the Swiss Light Source. It is a synchrotron-based platform that works in the EUV and soft X-ray wavelength region. It has a higher resolution compared to visible light microscopes thanks to its short wavelength and larger angle of incidence than the grazing incidence small angle X-ray scattering (GISAXS)<sup>5</sup> enabling a relatively small beam footprint on the sample. REGINE is a scatterometry, reflectometry and lensless imaging tool that uses a single ellipsoidal mirror to focus an EUV beam onto a vertically mounted sample surface. An in-vacuum CCD captures the reflected light from the sample plane. The sample image reconstruction will be performed using ptychography, a widely used scanning CDI technique.<sup>6</sup> The sample

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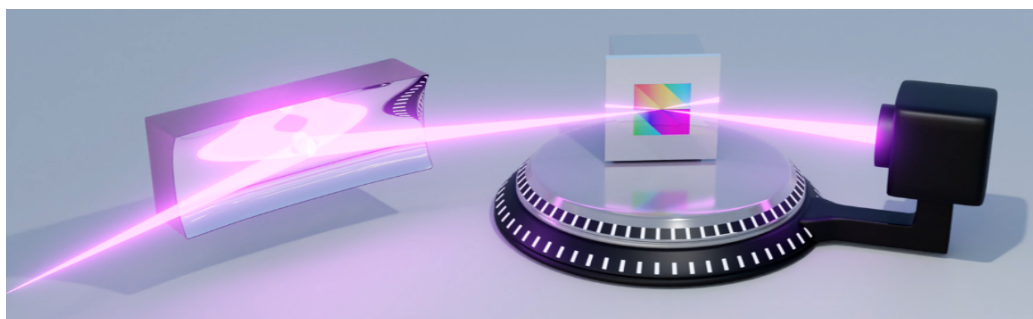


Figure 1: REGINE concept illustration. For better visualization purpose, the mirror is flipped 180° along the horizontal direction here.

and CCD are installed on two co-axially mounted rotation stages that can rotate independently. The concept of REGINE is shown in Figure 1.

The sample is mounted on an XYZ translation stage set that can provide a maximum scan area of 20 mm  $\times$  30 mm. Additionally, two interferometer sensors monitor the actual positions of the sample during a scan. A typical scan pattern we use is shown in Figure 2. In this case, we chose a meander scan and added a 10% random position error to the coordinates to mitigate the regular grid pathology often observed in ptychography reconstructed images.<sup>7</sup> Despite being relatively robust to noise, ptychography relies on the accurate measurement of the relative position between the illumination spot and the sample.<sup>8</sup> To minimize the reconstruction artifacts due to scan position uncertainty, we installed two interferometer sensors to monitor the X and Y position of the sample stage with an accuracy of 1 nm. In Figure 2 we show the difference between the position recorded by the sample stage encoders and the interferometric data.

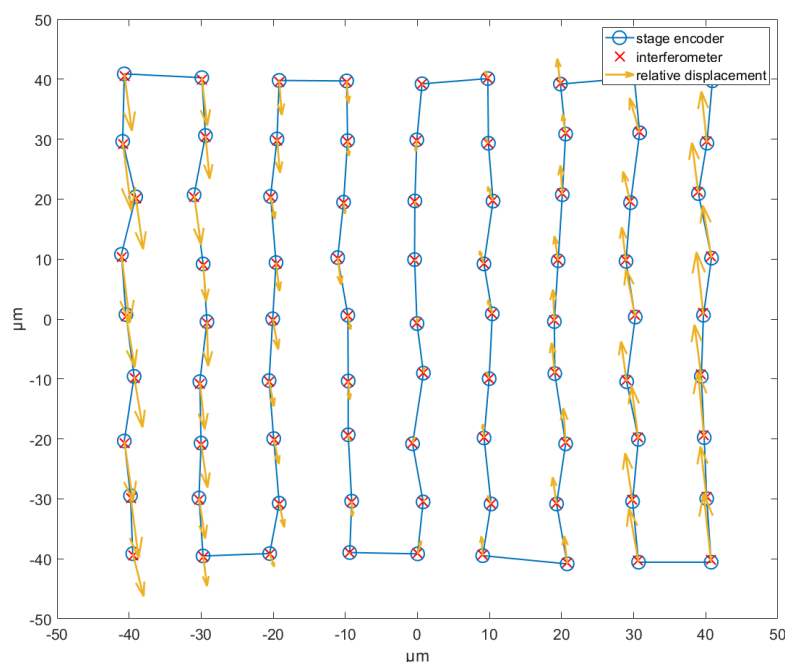


Figure 2: Meander scan pattern. The scan is referenced to the center position (0,0). The blue circles indicate the position values obtained from the stage encoders, and the red crosses are interferometer values. The difference between these two values is indicated by the yellow arrows.

REGINE is a multifunctional tool that integrates reflectometry, scatterometry and CDI. It is fully operational at the XIL beamline of the Swiss Light Source. The actual installation is shown in Figure 3.

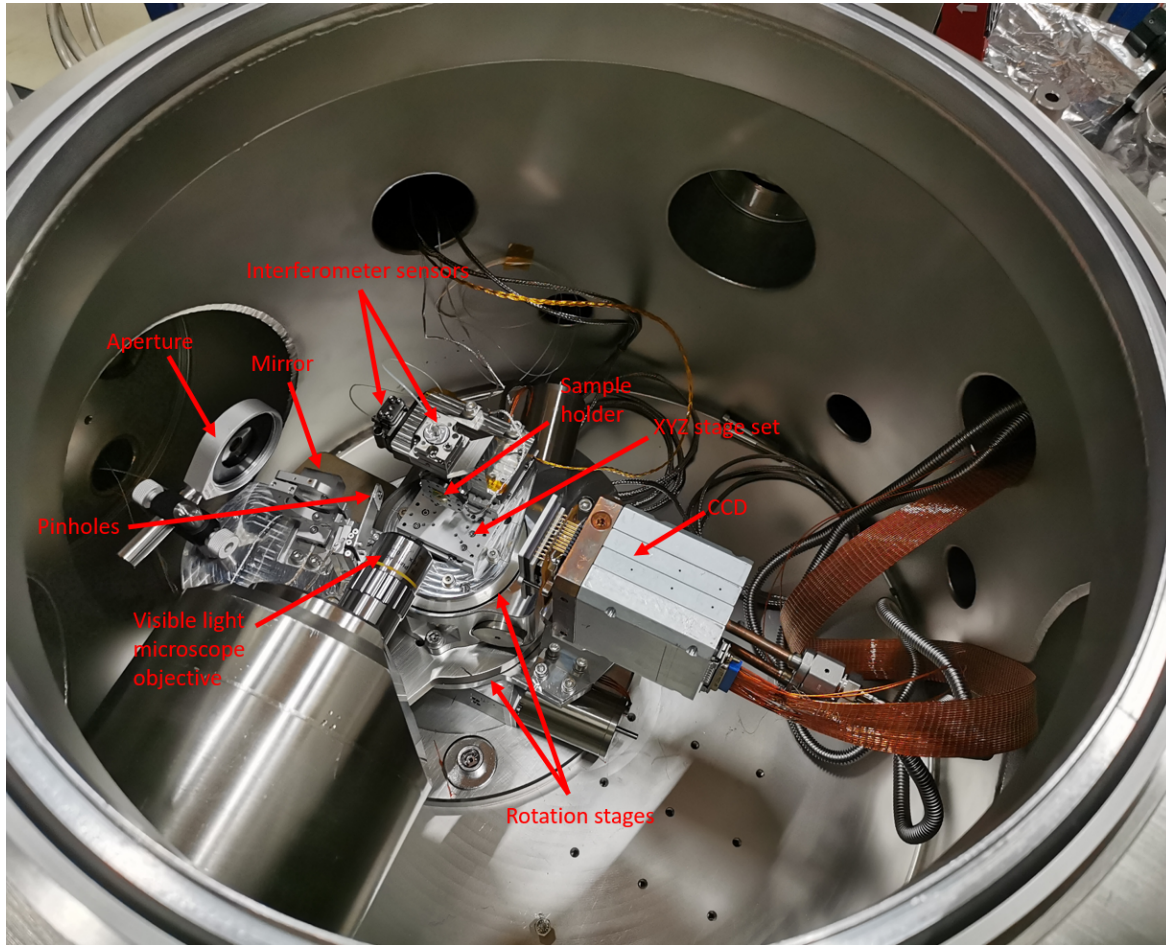


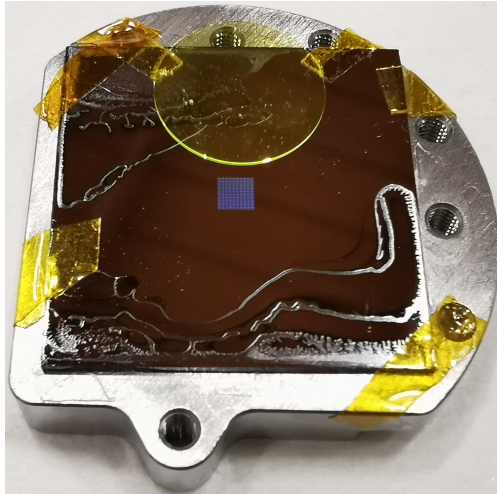
Figure 3: Installation of REGINE at the XIL beamline of the Swiss Light Source.

### 3. SYSTEM CHARACTERIZATION

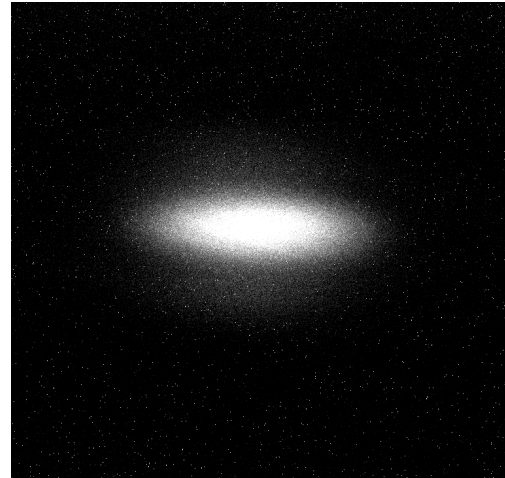
The use of the ellipsoidal mirror requires a careful system alignment. REGINE also equips a visible light microscope that looks at the sample plane as shown in Figure 3. Its field of view is centered on the intersection between the sample stage rotation axis and the incidence plane of the EUV beam. We attached a YAG crystal on the sample to observe the position and spot size of the EUV beam on the sample plane through the microscope as shown in Figure 4. This is intended to assist the system alignment procedure and to provide a more convenient sample navigation and alignment during the experiments.

After the alignment procedure was carried out with the YAG crystal, we verified the probe size using the diffracted signal. We scanned a diagonal grating across the probe on both horizontal (X) and vertical (Y) directions, and we recorded the diffraction patterns at each of the scan positions, as shown in Figure 5. Because of the Manhattan geometry of the sample, the diffraction peaks generated by the diagonal grating are easily identifiable. We selected the first diffraction order from the grating and we integrated its intensity in the recorded images as shown in Figure 5b. The evolution of the diffraction intensity is shown in Figure 6. The probe size equals the width of the Gaussian peak on the wafer plus the field size of the grating. Therefore, the probe on the sample plane has the size of  $51.98\text{ }\mu\text{m}$  and  $9.53\text{ }\mu\text{m}$  in the horizontal and vertical directions, respectively.



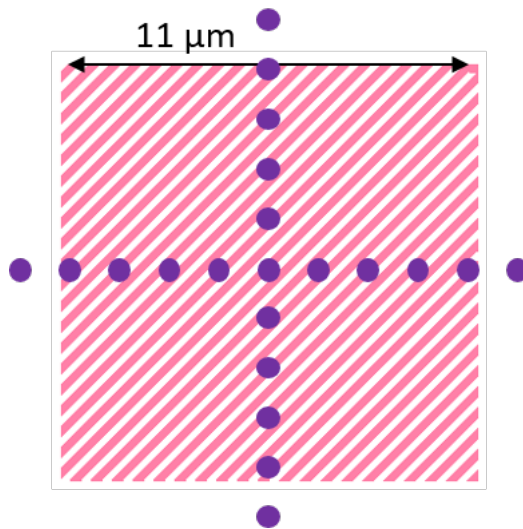


(a) Sample with YAG crystal attached

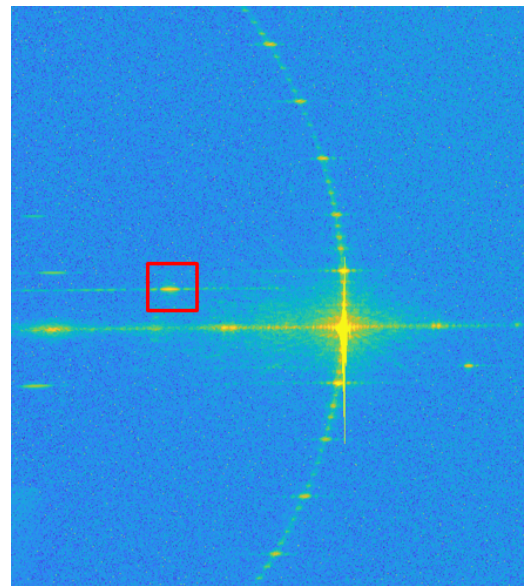


(b) EUV induced fluorescence on YAG crystal

Figure 4: A YAG crystal is attached on the sample to simplify the alignment procedure (a), and once the EUV beam is focused on the YAG crystal with a 25  $\mu\text{m}$  pinhole inserted before the sample, the fluorescence (b) can be observed under the microscope.



(a) Scan positions



(b) Diffraction pattern

Figure 5: The purple dots indicate the scan positions (a). Since the grating is not isolated, the recorded diffraction pattern is like (b), however, only the first order of the diagonal pattern (red square indicated) is used for calculation.

Fast implementations of ptychography, rely on the Fraunhofer or on the Fresnel approximation to model the propagation of the light from the sample plane to the detector plane. Because we work in reflection at a high incidence angle, the diffraction spectra that we record are mapped on a conical projection of the Ewald sphere and need to be corrected to be used in combination with the Fourier transform formalism that is the basis of our propagation models. This correction required precise knowledge of the probe incidence angle.<sup>9</sup>

In REGINE, we can measure the incidence angles, with a procedure similar to the one used for the probe size characterization. The sample was moved back and forth in the direction perpendicular to the sample plane

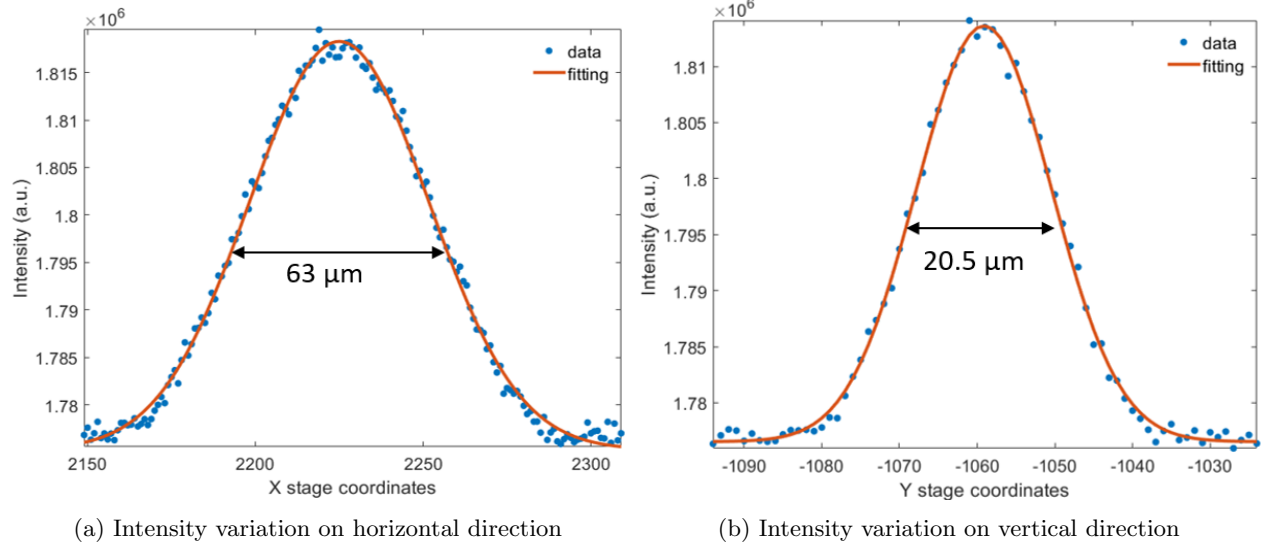


Figure 6: While scanning the probe across the diagonal grating, the total intensity variations in the red square indicated in Figure 5b on horizontal (a) and vertical (b) directions are fitted with a Gaussian function. The width of the Gaussian peaks is indicated, which equals the probe size plus the grating size.

(Z-direction), the beam spot on the sample surface, therefore, changes its relative position. By calculating the spot displacement and combining the sample movement on Z direction as shown in Figure 7, we obtained the incidence angles according to the Formula 1.

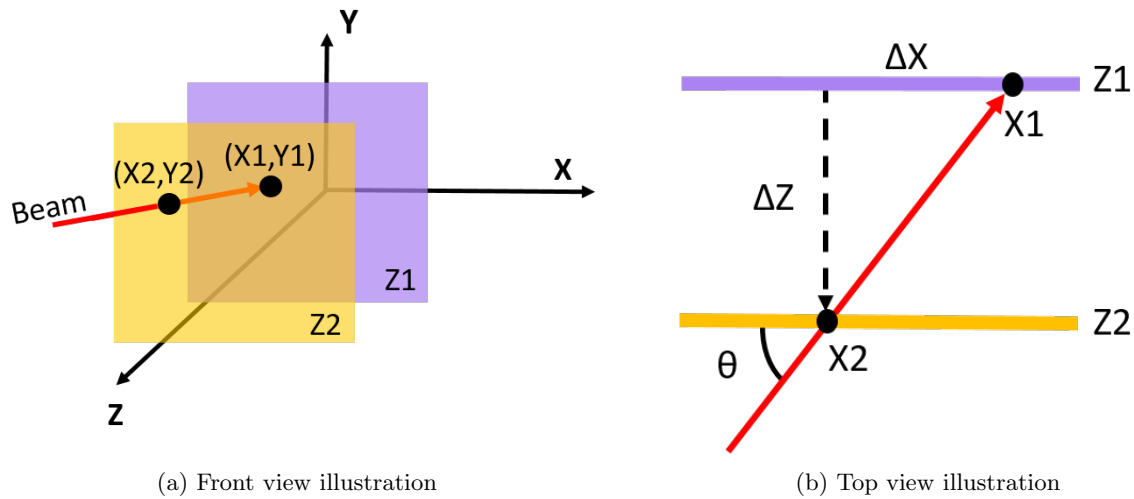


Figure 7: When the sample plane moved from Z1 to Z2, the beam spot changes its position on the sample plane (a), and (b) is the top view for the beam spot position change on X direction on the sample.

$$\Theta = \arctan \frac{\Delta Z}{\Delta X} \quad (1)$$

The measured angles are  $16.35^\circ$ ,  $86.42^\circ$ , and  $1.05^\circ$  on XZ, YZ and XY plane, respectively. These angles are used for the conical diffraction correction in Section 4.

## 4. EXPERIMENTS AND RESULTS

At the sample area shown in Figure 8, we performed a meander scan as illustrated in Figure 2. There are 81 scan positions in total and at each of the positions, we recorded 6 diffraction images with different exposure times (0.05s, 0.1s, 0.5s, 2s, 5s, 10s). These images were stitched together to get a high dynamic range image, which is shown in Figure 9. Due to the grazing incidence geometry, the image is distorted with the conical diffraction effect. For the standard ptychographic reconstruction, the conical diffraction has to be corrected. For the correction, we used the procedure described in<sup>10</sup> which yielded the spectrum shown in Figure 10.

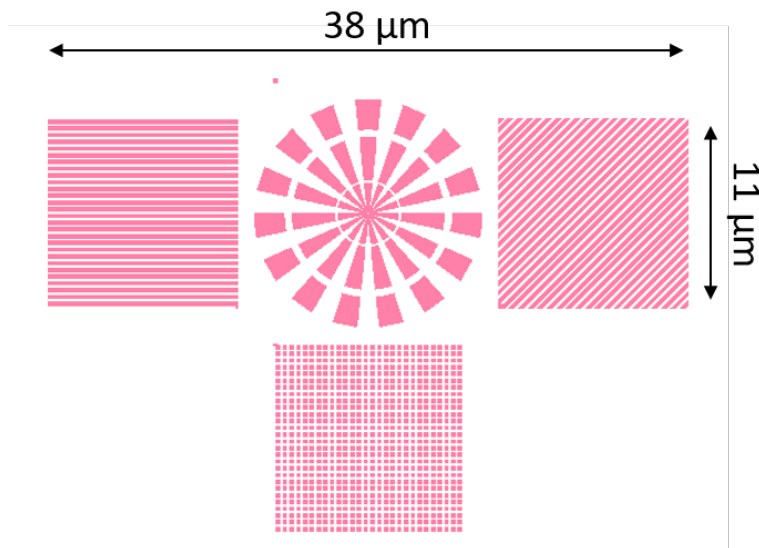


Figure 8: The sample has 140 nm tall HSQ pattern (Siemens Star and gratings) on top of Si/Mo multilayer. The gratings have a critical dimension of 200 nm.

## 5. CONCLUSIONS AND OUTLOOK

REGINE is a prototype nanoscope that integrates reflectometry, scatterometry, and CDI in a single tool for on-wafer metrology applications. It can efficiently collect high SNR scatterometry data and diffraction spectra. The possibility of changing both incidence angle and wavelength provides more redundant data for better reconstruction of geometrical parameters from the scatterometry data. Moreover, it enables tuning the penetration depth in CDI in order to gain information in 3D. We can also perform spatially resolved transmission measurements of thin films by mounting the sample on a 90° bracket. The relatively small probe size on the sample plane has still some potential for optimization, and therefore, one of our next steps is improving the alignment to get a probe size close to  $5\text{ }\mu\text{m} \times 5\text{ }\mu\text{m}$ . That will give us better coherence within the illumination area, and a higher illumination NA, and also higher spatial resolution for reflectometry and scatterometry experiments. Furthermore, we also planned scatterometry experiments for standard line-space gratings, and overlay grating targets. In the meantime, we are developing a more robust grazing incidence ptychographic reconstruction algorithm, and we intend to get a better reconstruction by using the data set as shown in Figure 10.

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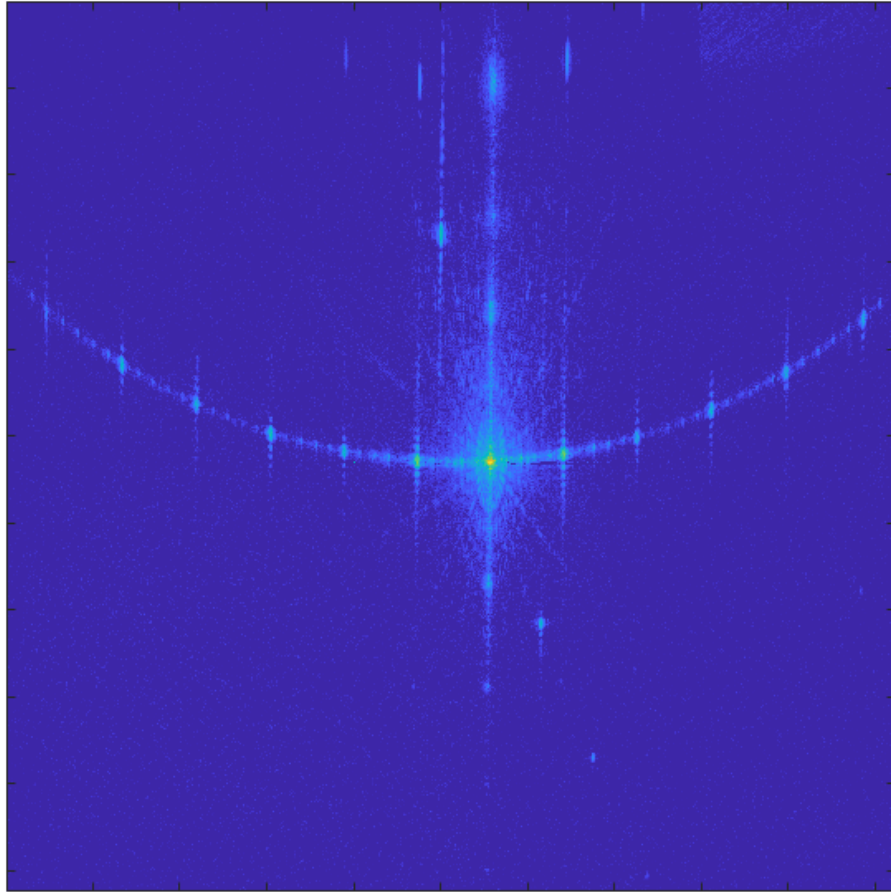


Figure 9: Raw image after stitching.

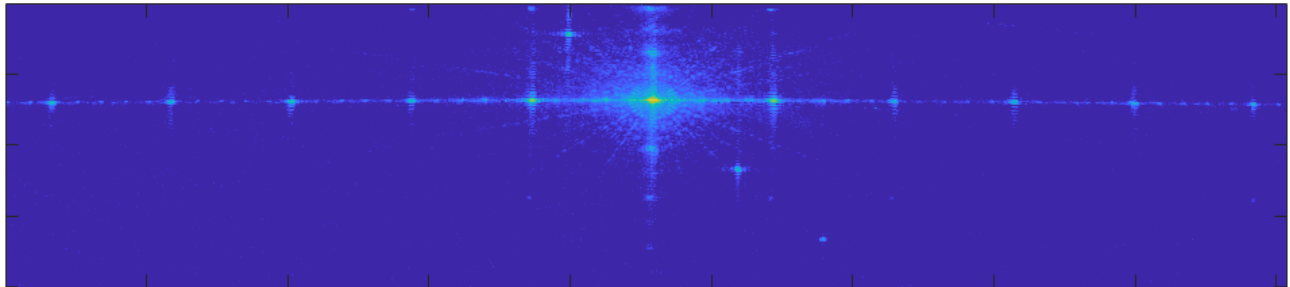


Figure 10: Corrected diffraction image.

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