Actinic inspection of EUV reticles with arbitrary pattern design

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ABSTRACT

The reflective-mode EUV mask scanning lensless imaging microscope (RESCAN) is being developed to provide actinic mask inspection capabilities for defects and patterns with high resolution and high throughput, for 7 nm node and beyond. Here we, will report on our progress and present the results on programmed defect detection on random, logic-like patterns. The defects we investigated range from 200 nm to 50 nm size on the mask. We demonstrated the ability of RESCAN to detect these defects in die-to-die and die-to-database mode with a high signal to noise ratio. We also describe future plans for the upgrades to increase the resolution, the sensitivity, and the inspection speed of the demo tool.

Keywords: Defect inspection, pattern inspection, actinic inspection, EUV lithography, coherent diffraction imaging, lensless imaging

1. INTRODUCTION

Actinic pattern inspection on EUV reticles is considered an essential tool for the implementation of EUV lithography in high-volume manufacturing. Nevertheless, there is currently no long-term solution available for it. The main challenges for any mask defect inspection platform are resolution and sensitivity. The reflective-mode EUV mask scanning lensless imaging microscope (RESCAN) is being developed to provide actinic mask inspection capabilities for defects and patterns with high resolution and high throughput, for 7 nm node and beyond.

RESCAN is a lensless tool and relies on coherent diffraction analysis to retrieve information about the reticle and the defects. Since this approach does not need imaging optics, it is not affected by aberrations, it is not limited by the depth of focus and it is easily scalable for future technology nodes.

In previous studies,¹⁻³ we demonstrated that RESCAN can detect programmed defects on periodic absorber structures. In this study, we report on the inspection of programmed defects on non-periodic, random patterns. Here, we show die-to-die and die-to-database inspection down to 50 nm programmed defects.

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Figure 1. The prototype of the RESCAN platform, operating at the Swiss Light Source. The panel on the left shows a rendering of RESCAN. The optical layout of the tool is shown on the right. The beam from the XIL-II beamline reaches the spherical condenser mirror M1 that focuses it. The beam is folded onto the sample at an angle of incidence of 6° by the flat mirror M2. The far-field diffraction pattern is then recorded by the detector.

2. METHODS

2.1 RESCAN description

RESCAN is installed in a compact vacuum chamber at the XIL-II beamline at the Swiss Light Source. The beamline is optimized for maximum efficiency at a wavelength $\lambda = 13.5$ nm, and it is equipped with a monochromator that allows to control the bandwidth and the wavelength of the illumination beam. The maximum monochromaticity available is $\lambda/\Delta\lambda = 1800$. The current optical layout of RESCAN is shown in the right panel of figure 1: the light coming from the synchrotron reaches a spherical condenser mirror (M1) and is focused on the sample with a 6° angle of incidence (AOI) through a flat folding mirror (M2). The sample is held on a XY piezo stage with $200\text{ }\mu\text{m}$ range and a precision of ± 5 nm. The far-field diffraction pattern is captured by an EUV-CCD detector and it is used to reconstruct the image of the sample by means of a coherent diffraction imaging (CDI) algorithm. The CCD is placed at a distance of 57 mm from the sample, it has 2048×2048 pixels and an area of 27.6×27.6 mm². The corresponding numerical aperture (NA), calculated over the largest circular aperture inscribable in the detector, is therefore $\text{NA} = 0.24$ and it determines the resolution limit of the current setup:

$$R \simeq \frac{1.22 \cdot \lambda}{2\text{NA}} = 35 \text{ nm}. \quad (1)$$

2.2 Reconstruction algorithm

The mode of operation of RESCAN depends on the characteristics of the sample. The defect detection is performed by scanning the reticle with a coherent EUV beam and recording the diffraction patterns with high NA. The diffraction patterns are compared to simulations or to data previously collected over a defect-free test pattern to detect the presence of defects.¹ Using this approach, we have successfully demonstrated how RESCAN is capable of detecting amplitude defects on periodic structures.² The application of this method for the detection of defects on random logic patterns has been proved in simulation, but suffers from technological limitations that make it difficult to carry out an experimental demonstration with a research tool like RESCAN. The detection sensitivity is severely hampered by the accuracy of the sample stage and by the stability of the EUV light probe position on the sample. These two parameters are

affected by mechanical vibrations that induce an uncertainty $\sigma \geq 10$ nm in the relative position of the sample and the probe. This uncertainty induces a noise that is of the same order of the signal generated by most defects. This shortcoming can be overcome by turning to a full CDI approach.

To reconstruct the complex amplitude of the sample, we developed a CDI algorithm based on ptychography.³ In the recent years, thanks to the increasing availability of computational power, the use of CDI techniques has become more and more prominent in the areas in which traditional optical solutions are expensive or technologically challenging such as EUV and X-Ray imaging.⁴ Among the different CDI techniques, ptychography proved to be particularly robust and efficient and has been developed extensively.^{5,6} In a traditional optical system, a sample is illuminated by a light source, a lens collects the diffracted light and recombines it to form an image. In *lensless* imaging systems instead, a detector is placed in the lens plane and the image of the sample is reconstructed computationally from the recorded diffraction pattern. The recorded diffraction pattern is the magnitude of the electromagnetic field in the lens plane, but the phase information is usually lost, making it impossible to solve the inverse problem and thus retrieve the image of the sample without additional information. In ptychography, the sample is scanned with a coherent beam with a finite footprint that we shall call *probe*, and for each position of the probe a diffraction pattern is recorded. The scanning step size is such that the probes have a certain amount of overlapping. To solve the inverse problem, ptychography iteratively searches for a common solution in the overlapping regions. In other words, the missing phase information is retrieved from the redundancy generated by the overlapping of the probes.

The general mathematical formalism of the reconstruction algorithm has been thoroughly described elsewhere,⁵ but it is worth noticing that in our specific application it is essential to maximize the reconstruction speed. For this reason, the sampling of the diffraction pattern is a decisive parameter. Let $S(\vec{r})$ and $P(\vec{r})$ be the complex amplitude of the sample and of the probe respectively. For each position of the probe $\vec{r}_j$, we can define a *view* ψ_j as:

$$\psi_j = S(\vec{r}) \cdot P(\vec{r} - \vec{r}_j). \quad (2)$$

An essential step in the reconstruction algorithm is to enforce an intensity constraint by setting the magnitude of the diffraction pattern relative to each view to the quantity I measured with the detector.

$$I_j = |\mathcal{F}\psi_j|^2 \quad (3)$$

where $\mathcal{F}$ is the Fourier transform operator. Since ψ does not extend further than the region defined by the probe P , it is useful to constrain the sampling of the Fourier transform to match the size of the probe, when the latter is known. This choice minimizes the calculation speed, maximizes the signal to noise ratio and avoids aliasing effects that can lead to misinterpretations of the reconstructed image.

2.3 Programmed defect sample description

To test the limits and to demonstrate the potential of RESCAN, we developed a test sample with programmed defects embedded in logic-like random patterns. The defects size ranges from 200 nm to 50 nm on the mask.

The sample's core layout is shown in figure 2; it consists of a 50 μm square unit cell with a 200 nm CD random pattern. The pattern includes also 400-nm horizontal power rails with 4.1 μm pitch. Since RESCAN does not have any auxiliary visible-light microscope to help with the sample navigation, we added eight gratings to identify the inspection area: the gratings diffraction pattern is easily identifiable and allows us to determine the position of the sample with a

precision of a $\pm 2 \mu\text{m}$, comparable to the size of the illumination probe.

For each defect size, we placed a reference unit cell next to a defective one and we replicated this design over an area of $2 \times 2 \text{ mm}^2$. With this arrangement, the reference and the defective field are both within the range of the sample stage and this allows us to perform a die-to-die defect inspection without re-mounting and aligning the sample.

Figure 2. The unit cell of the random pattern we generated is represented on the left. It consists of a dark-field random pattern with a critical dimension of 200 nm overlapping an horizontal grid of power rails of 400 nm width. The central zone of the pattern, shown in the center, is surrounded by four alignment gratings. The central feature shown on the right is a control structure on which we superimpose extrusion defects (showed in red) of different sizes.

The sample substrate is a silicon wafer with a MoSi multilayer designed for maximum reflectivity at 6° incidence and 13.5 nm wavelength. The absorber consists of a hydrogen silsesquioxane (HSQ) layer deposited by spin-coating. The pattern was recorded on the HSQ layer by electron beam lithography using a Vistec EBPG 5000+ES system operated at 100 keV. The sample has been exposed with an e-beam dose of $4500 \mu\text{C}/\text{cm}^2$ and developed in a Microposit^{TM}351 solution (1:3 in water) for 150 s. The quality of the pattern can be evaluated from the SEM images of the defects shown in figure 3. The size uncertainty of the extrusion defects is approximately 0.5%.

The absorption coefficient of HSQ at 13.5 nm for an incidence angle $\theta = 6^\circ$ is $\alpha = 0.0991 \mu\text{m}$.⁷ Since the thickness of the absorber layer is $h = 145 \text{ nm}$, we can expect a 3% double pass transmission through it. The density and composition of HSQ after e-beam exposure largely depends on the development parameters. We can assume that the density of the developed film will be between $1.57 \text{ g}/\text{cm}^3$ and $2.17 \text{ g}/\text{cm}^3$.⁸ The corresponding refraction indexes at 13.5 nm are $n = 0.9843$ and $n = 0.9781$ respectively.⁷ The phase difference between regions of the sample with and without absorber can be calculated as:

$$\Delta\phi = \frac{4\pi h}{\lambda} \left(\frac{1}{\cos\theta} - \frac{n^2}{\sqrt{n^2 - \sin^2\theta}} \right) = \begin{cases} 2.11 \text{ rad}; & \delta = 1.57 \text{ g}/\text{cm}^3, \quad n = 0.9843 \\ 2.94 \text{ rad}; & \delta = 2.17 \text{ g}/\text{cm}^3, \quad n = 0.9781 \end{cases} \quad (4)$$

These results suggest that we can expect this sample to have a high phase contrast.

Figure 3. These images are SEM scans of the extrusion defects we added to the control structure. The extrusions sizes are $200 \times 200 \text{ nm}^2$, $200 \times 150 \text{ nm}^2$, $200 \times 100 \text{ nm}^2$ and $200 \times 50 \text{ nm}^2$.

3. RESULTS: LOGIC PATTERN INSPECTION

Mask defect inspection can be carried out in die-to-die (D2D) or die-to-database (D2DB) mode. In D2D mode, a defect-free region of the sample is inspected and compared to another identical region. Defects show up in as differences in the comparison between the two measurements. In D2DB mode, the reconstructed image of the sample is compared to an aerial image obtained from the reticle's layout.

3.1 Die-to-Die inspection

D2D inspection in RESCAN is quite straightforward. We inspect a reference cell and a neighboring defective cell, we align the reconstructed images performing a sub-pixel registration,⁹ we scale their magnitude to correct for background intensity variations and subtract the reference image from the test one so that extrusion defects appear as a positive signal in the difference image. Figure 4 shows the results of the die to die inspection performed on the $200 \times 200 \text{ nm}$ extrusion defect. The difference image shows the presence of the extrusion defect and a low-contrast contour of the reference pattern attributable to artifacts in the reconstruction and to the physical pattern size uncertainties. The strength of the defect signal has been estimated in terms of signal to noise ratio defined as follows:

$$\text{SNR} = \frac{\bar{I}_D - \bar{I}_A}{\text{std}(A)} = 15.2, \quad (5)$$

where $\bar{I}_D$ and $\bar{I}_A$ are the average magnitude values calculated on the defect area and on the whole image respectively, while $\text{std}(A)$ is the standard deviation of the magnitude of the image. Note that this definition of the SNR does not depend directly on the area of the defect.

Figure 4. In D2D inspection mode a reference field is inspected and compared to the corresponding defective field. The image on the left is the reconstructed magnitude of a reference field and the one in the middle is the reconstructed magnitude of the corresponding field with a $200 \times 200 \text{ nm}^2$ extrusion. The right image is the comparison of the two fields where the defect stands out.

Although the structures we studied include only pattern defects, the sample has a large phase contrast as predicted in equation 4 and confirmed by the phase reconstructions in figure 5. The phase difference of the reconstructed image was calculated by subtracting the average phase recorded over the absorber area and the average phase recorded over the clear region. In the case of the image shown in figure 5 we measured a $\Delta\phi = 2.1 \pm 0.6$, within the limits of the theoretical prediction derived in equation 4.

Figure 5. The image on the left is the reconstructed phase of a reference field and the one in the middle is the reconstructed phase of the corresponding field with a $200 \times 200 \text{ nm}$ extrusion. The right image shows the comparison of the two fields.

3.2 Die-to-Database inspection

In many cases, the pattern redundancy in EUV reticles makes it possible to perform defect inspection in D2D mode, but for large chips that encompass the entire image field, D2DB inspection becomes necessary.¹⁰

IN D2DB mode, we need to calculate the mask image starting from the physical layout of the sample. In this case, we used an extremely simple simulation approach that consist in applying a spatial frequency filter to the reticle binary layout (figure 6). This solution is extremely fast, but neglects the effects of the sample topography and its physical properties. Nevertheless it proved to be sufficient to detect the programmed defects down to a size of 50 nm as shown in figures 6

and 7. The spatial frequency filter we used is a square aperture with a size corresponding to solid angle defined by the CCD detector which corresponds to 0.48 in normalized pupil coordinates. The filtered layout image is then translated and rotated with a transformation matrix calculated to minimize the pattern difference error. Finally, the reference image is uniformly scaled to match the magnitude of the reconstructed one. The two images are compared as in the D2D case to retrieve the defect signal.

Figure 6. In die-to-database inspection the reconstructed image magnitude is compared to the magnitude of the aerial image calculated from the sample GDS. The image on the left is the sample layout. We applied a spatial frequency filter corresponding to the NA of the system to the image layout to estimate the aerial image magnitude shown in the middle. On the right we show the comparison between the reconstructed image and the estimated aerial image magnitude.

In the top row of figure 7, we show the area of the four defects as it appears in the image difference, (see the right panel of figure 6). The reported SNR value was calculated as described in 3.1. In the bottom row we report the corresponding defect map obtained by applying a uniform threshold to the images.

4. CONCLUSIONS AND OUTLOOK

We used the current prototype of RESCAN to inspect dedicated samples with programmed defects on random, non-periodic patterns. We proved that RESCAN can successfully operate in die-to-die and die-to-database mode detecting defects with a size on mask of 50 nm or smaller, with a high signal-to-noise ratio as shown in figure 8.

While the results presented here show the potential of CDI for actinic pattern inspection, the hardware and the software of the RESCAN platform can be still significantly upgraded.

Even though we proved that RESCAN can detect defects down to 50 nm in size in D2DB mode, our current simulation approach can be greatly improved. To this end, we intend to implement a fast, but reliable method to calculate the expected aerial image that can take into account the 3D structure of the reticle stack. For low accuracy, the angular spectrum propagation method¹¹ is a valid solution. In cases where higher image fidelity is required we will switch to more advanced techniques.¹²

On the hardware front, the current detector used in RESCAN has a 16-bit dynamic range, which is insufficient to record the full diffraction pattern generated by an average random sample and the chosen illumination probe. To overcome this limitation we sacrifice a portion of the available flux to avoid saturation in the most intense regions of the diffraction pattern and we collect up to five images with increasing exposure times that we stitch together to achieve the

Figure 7. Die-to-database inspection of different size extrusion defects. The top row images are the representations of the defects in the comparison between the reconstructed sample and the estimated aerial image magnitude. The images are plotted in the same color scale. The defect maps in the bottom row were obtained by applying an uniform threshold to the previous images.

Figure 8. Signal-to-noise ratio as a function of defect size in Die-to-Database inspection mode.

required dynamic range. This procedure increases both the acquisition and the computation time and it is not fit for applications that require high throughput like mask defect inspection. The necessity for high dynamic range is a well documented problem in ptychography applications. In some cases it is possible to increase the dynamic range using a semi transparent central stop to dampen the intensity of the scattered light in the low frequency-region.¹³ Unfortunately, this approach fails with samples that include highly periodic features, where high-intensity diffraction peaks are observed at high frequencies as well. In general, it is convenient to operate with a high NA illumination probe in order to spread out the energy of the diffraction peaks.¹⁴ The solution we chose for RESCAN is to adopt the JUNGFRÄU (adJUStiNg Gain detector FoR the Aramis User station), a modular high dynamic-range detector with an acquisition frame rate that can reach 2000 Hz.^{15,16} As a next step, we plan to install a Jungfrau detector with two modules of 512×1024 -pixel and EUV optimized sensors with $75 \mu\text{m}$ pixel size. This will allow us to

increase the NA of RESCAN from 0.24 to 0.4 and to bring its resolution down to 20 nm. The high-dynamic range of this detector, in combination with the optimization of the illumination NA, will allow us to collect a whole diffraction pattern in a single acquisition without sacrificing flux which is an essential step towards the development of an industrial actinic inspection tool.

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