COHERENT DIFFRACTIVE IMAGING

Semiconductor features such as transistors used in computer chips have reached the nanometer scale, yet metrology tools still have to follow the advances in the industry to study this new generation of chips. Short-wavelength microscopy using extreme ultraviolet (EUV) light or soft X-rays could offer a solution, but it is not compatible with conventional imaging optics. Researchers from Delft University of Technology have built a lensless microscope that uses coherent EUV light to make an image at the scale of 100 nm. With further refining of this technique, they expect to drastically improve the resolution, possibly down to wavelength scales.

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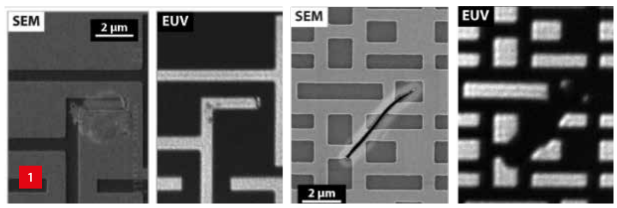
Introduction

The quest for lensless microscopy with extreme ultraviolet (EUV) and soft X-rays (SXR) originated from the need for short-wavelength (roughly below 20 nm) microscopy. A conventional microscope uses a set of lenses, arranged in such a way that they can magnify extremely small objects. The smallest feature one can observe with such a device is typically defined by the quality of the lenses and the wavelength of the light used to illuminate the sample. This is the so-called diffraction limit or Abbe limit, which is defined as $d = \lambda/(2 \cdot NA)$, where d is the resolution, λ is the wavelength and NA (numerical aperture) indicates the quality of the optics.

Improving the resolution is obviously of interest for many applications, but in particular for optical metrology in the semiconductor industry. The continuous innovation in this industry reduces the dimensions of structures in next-gen chips and thus increases the resolution requirements for metrology tools. Consequently, this wavelength-dependent diffraction limit is obviously a good reason to use shorter wavelengths.

If resolution is the main driver, then why not use electron microscopy, as this is an already well-adopted and matured tool? Besides resolution, optical contrast is of importance, especially for lithography mask metrology, for example. The masks involved are exposed to EUV light (13.5 nm) in advanced lithography scanners and project the structures in the mask onto a wafer. If they contain defects, these are transferred via the EUV light to the wafer and could potentially ruin the product. Therefore, one would ideally like to know what the defects look like under EUV light, so-called actinic metrology, as they can look vastly different in different metrology tools; see Figure 1.



Defects in semiconductor samples can look vastly different depending on which metrology tool is used. (Image source: [1])

So, why not use the smallest wavelength possible and go all the way down to EUV, X-rays or gamma rays for high-end microscopy? Unfortunately, fabricating optics for these wavelengths is quite a challenge. Conventional refractive optics do not exist in this regime (with some exceptions [2]), so we have to resort to other types of optics. Diffractive optics, such as Fresnel zone plates, and reflective optics can be used, but are exceptionally hard to manufacture in a high-*NA* version.

As an indication, the advanced optical system of ASML's EUV scanners is based on a set of mirrors with an *NA* of 0.33 (which will be improved to 0.55 [3]). While ASML's deep-UV immersion scanner, which still works with refractive lenses, has an *NA* of 1.35. Although these are not metrology tools, it does demonstrate that reaching a high *NA* with EUV is a major challenge.

Lensless imaging, particularly ptychography (see below), can be an exciting approach to bypass this issue for next-generation metrology tools and extract the potential that EUV and SXR light can offer to the industry.

Lensless imaging

In a conventional microscope, an object of interest is illuminated with a light probe and part of the light is

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reflected and diffracted by the sample. This light is captured by a set of lenses (or mirrors) and transformed into an image on a camera or an observer's eye. Now if this were repeated without any lenses, the electric field E of the light beam would freely propagate towards the camera; see Figure 2. This propagation of the electric field can be described as:

$$E(x,y,z) = \iint \frac{1}{i\lambda}\frac{e^{ikr}}{r} E_0(x_0,y_0,z_0)dxdy$$

Here, E_0 refers to the electric field at the sample and r is the observation location in x,y,z space, i.e. the location of the camera:

$$r = \sqrt{(z-z_0)^2 + (x-x_0)^2 + (y-y_0)^2}$$

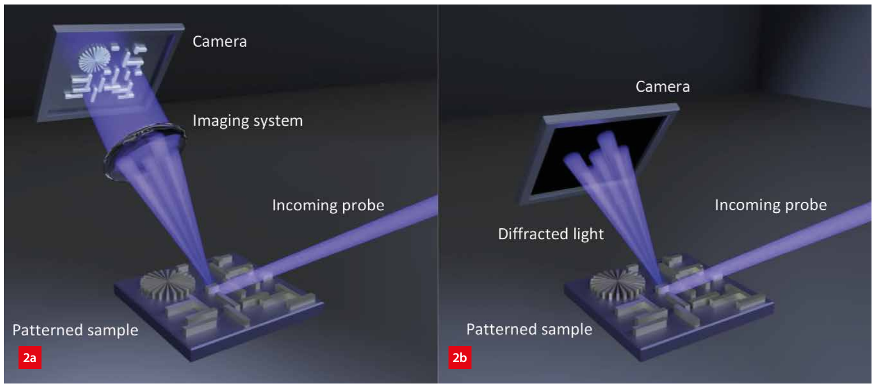
If the camera is sufficiently far away from the sample, meaning z becomes sufficiently large, these equations approach a 2D Fourier transform of the light that originated from the sample.

The diffraction patterns contain amplitude and phase information, both of which are needed to be able to perform an inverse Fourier transform and resolve the sample. However, cameras can only register intensity, so that the phase information is lost. It has been shown previously [4] that the phase can be retrieved via an iterative phase-retrieval algorithm. Loosely said, a suitable phase is found by fitting/optimising via iterations between Fourier space and real space. Imaging methods based on this concept are often referred to as coherent diffractive imaging (CDI).

CDI can be extended by scanning the probe across the sample and acquiring multiple diffraction patterns. By overlapping the probe at different scanning locations, we ensure that diffraction patterns acquired at neighbouring locations share information. This results in ambiguities, which reduce the number of solutions in the optimisation algorithm and make the reconstruction more robust. This approach is commonly known as ptychography and it has shown great potential in recent publications [5]. We have developed our own ptychography reconstruction algorithm, which is outside the scope of this article.

High harmonic generation

In order to perform ptychography and capture sets of diffraction patterns, the sample has to be illuminated with spatially and temporally coherent EUV light. Typically, researchers resort to large facilities such as synchrotrons or free-electron lasers (FELs) for obtaining laser-like EUV



Two ways of capturing diffracted light.
(a) Conventional imaging: using an optical (imaging) system to create an image on a camera.
(b) Lensless imaging: the optical system is removed and the diffracted light is captured directly.

light. Unfortunately, this is out of reach for many research or industry applications. However, enormous advances in table-top coherent EUV sources have made them commercially available, making it a viable solution for most applications with these requirements.

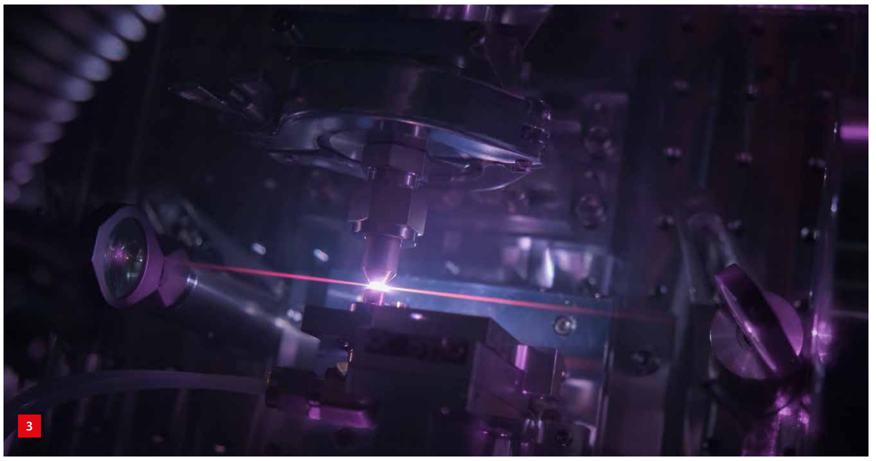
The sources are based on high harmonic generation (HHG), which is achieved by focusing a high-power laser with pulses of a few femtoseconds (fs) on a gas jet. The electric field in the focus is sufficiently large to distort the potential well of these noble-gas atoms to such an extent that electrons can tunnel out of this well and the atom is essentially ionised. The electric field accelerates the electron away from the parent ion. Eventually, the electric field of the light pulse flips and the electron starts to decelerate and then accelerate again back towards the parent ion with considerable additional kinetic energy.

If the electron recombines with the ion, it releases this additional energy in the form of light. This light contains multiple harmonics of the fundamental drive-laser frequency, leading to a frequency-comb-like response of odd harmonics (i.e. $n = 1, 3, 5, 7$, etc.). By combining the individual responses of a collective of atoms, it becomes possible to generate coherent light through phase matching.

The EUV system is driven by a 1,030-nm infrared (IR) Ytterbium fibre laser (Active Fiber Systems) with an average power of 100 W running at a repetition rate of 600 kHz and a pulse length of 300 fs. These pulses are compressed to ~30 fs with an efficiency of 70% and focused onto a pressurised noble-gas jet (Figure 3). Higher harmonics are generated (depending on the drive gas) up to 140 eV (~9 nm). The wavelengths of interest for our applications are 68 eV (18 nm) and 92 eV (13.5 nm), with photon fluxes of $1 \cdot 10^{11}$ and $0.5 \cdot 10^{9}$ photons per second, respectively.

The residual high-power IR light needs to be removed after the low-power EUV and SXR light has been generated. A set of grazing-incidence plates set at the Brewster angle of the IR light help to get rid of the majority of the IR light. A few free-standing aluminium or zirconium foils with a thickness of 200 nm remove the last remainder of IR light.

The EUV beam contains a wide range of harmonics, up to the ~110th harmonic (for 9 nm wavelength), see Figure 4. As mentioned before, preferably temporally coherent light is produced, so that a single harmonic is ideally isolated (although this is not strictly necessary). The metallic foils used as an IR filter already reduce the bandwidth down to tens of harmonics. A set of multi-layer mirrors, set at an angle of 45°, select a narrow bandwidth of 0.6 nm at 18 nm (or 13.5 nm) with a combined peak reflectivity of 20%.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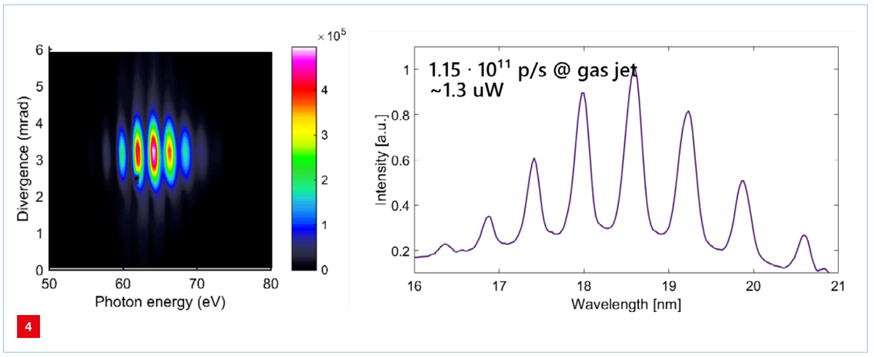
Coherent EUV and SXR light can be generated by focusing high-power IR light into a noble-gas jet. This ionises the atoms in the gas jet leading to a beautiful plasma being displayed.

Beamline realisation

After spectral filtering, the beam is focused onto a sample via an ellipsoidal mirror. The EUV beam hits the curved mirror at a grazing incidence of 10° (relative to the surface) for sufficient reflectivity. With a rather rough alignment of the ellipsoidal mirror, a probe of 50 µm x 80 µm has been achieved. This relatively large probe size limits the expected resolution of the microscope to about 80 nm. Improving the optical alignment of the ellipsoidal mirror should yield a reduced probe size and therefore push the resolution further down, potentially to the wavelength regime.



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The high harmonics can be optimised in a certain bandwidth through phase matching, in this case (argon drive gas, 1.3 µW flux observed) around 18 nm.

Downstream of the ellipsoidal mirror, there is an assembly of stages containing the sample holder and the camera. A sample is mounted in a custom-built 5-DoF (degrees of freedom) stage. This allows for lateral (x,y), angle of incidence (θ), azimuth (ϕ) and depth (z) sweeps during the ptychography experiments. The large range and accuracy of slip-stick piezo stages enable the scanning of samples of 20 mm x 20 mm with a few nm positioning accuracy. A full-vacuum EUV camera (PI-MTE3 2048x2048) is mounted on a rotation stage to allow adjustments in the angle of incidence on the sample. Figure 5 shows the complete system.

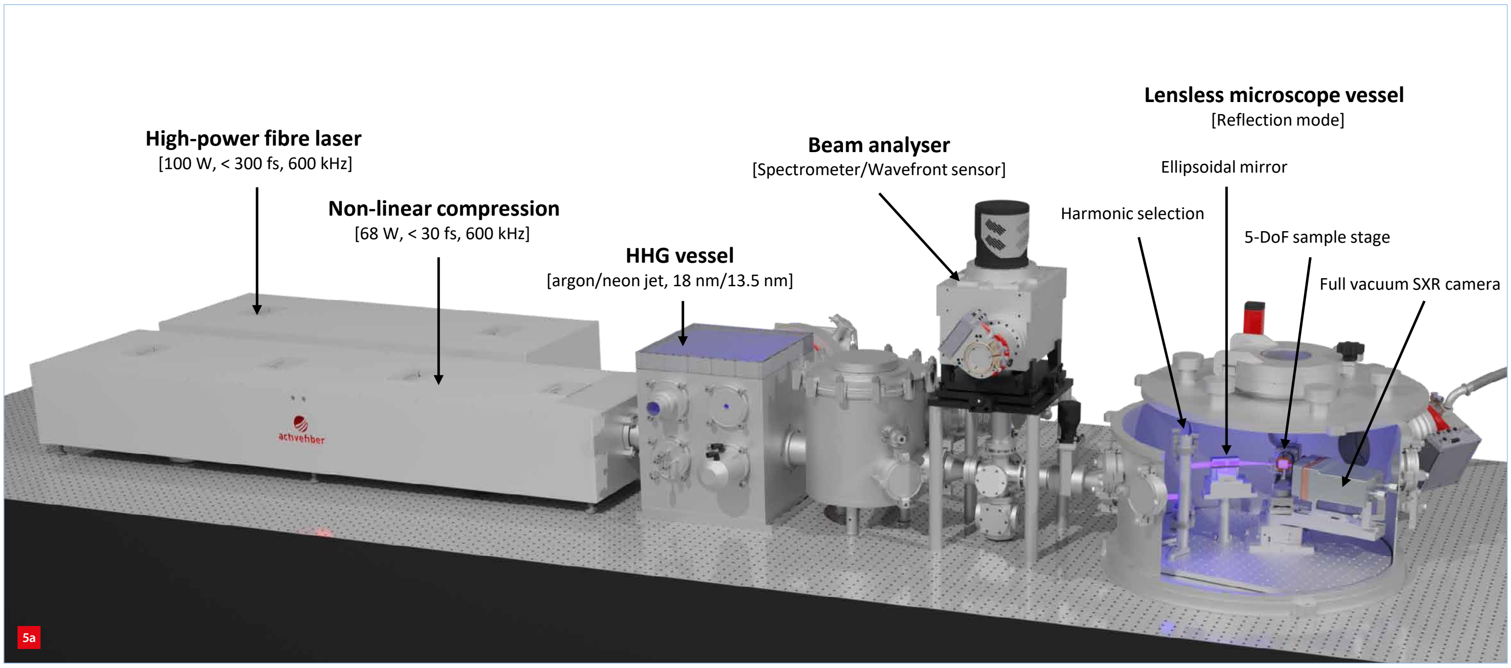
With all the ingredients available, a first test run was performed. This run consisted of a 2D grid pattern with intentional perturbations on a silicon sample with gold structures ranging from 500 nm down to 10 nm at an angle of incidence of 20° relative to the surface. In total, 225 frames have been acquired with an exposure time of 200 ms per frame and a total exposed area of 70 µm x 260 µm. Thus, excluding camera read-out rates and stage movement time, an imaging rate of about 400 µm^2/s is achieved.

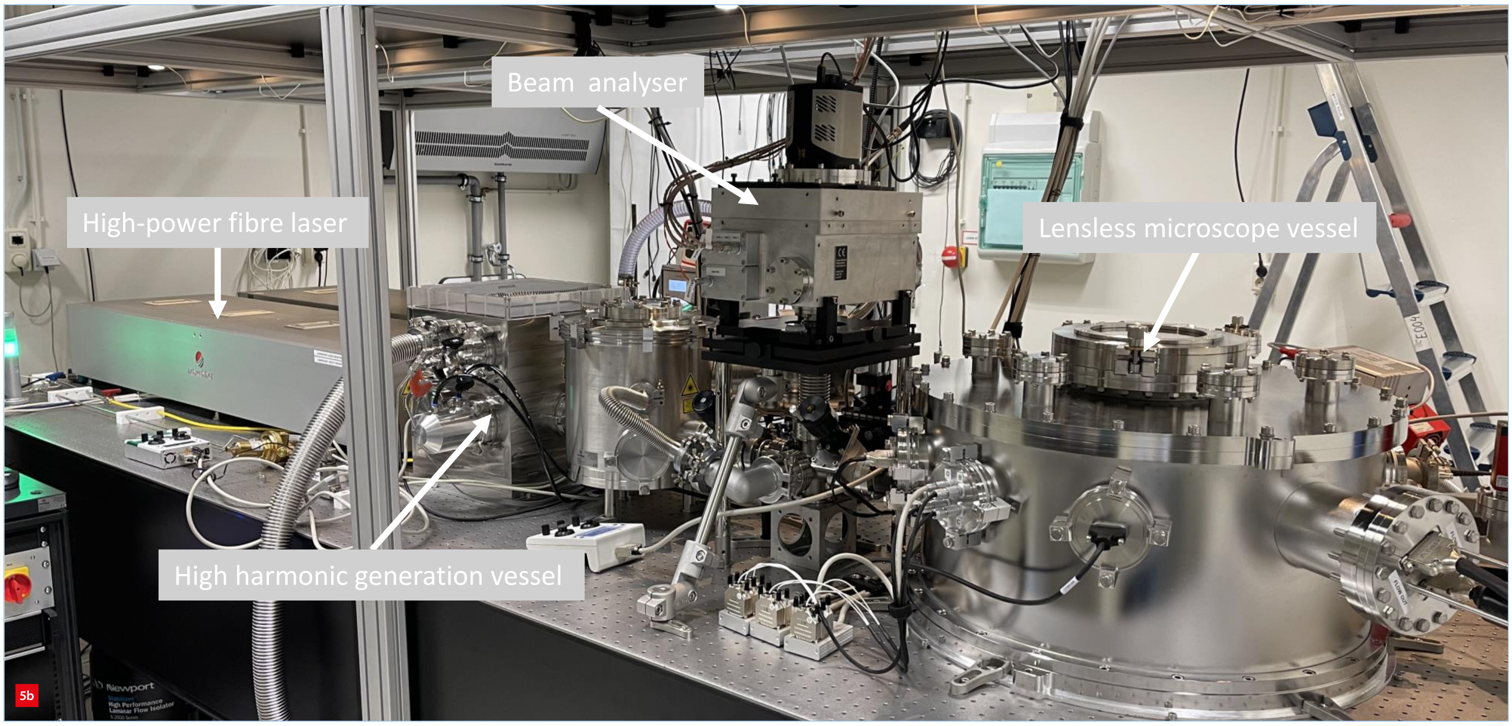
With these 225 diffraction patterns and the advanced reconstruction algorithm, both a complex sample and probe can be resolved. Linear gratings with a pitch of 100 nm have been resolved indicating that the resolution is at least 100 nm, very close to the expected limit of 80 nm. As a complex image, i.e. reflection function and phase function, can be retrieved, it is possible to retrieve material information and height of the structures, as shown in Figure 6.

Outlook

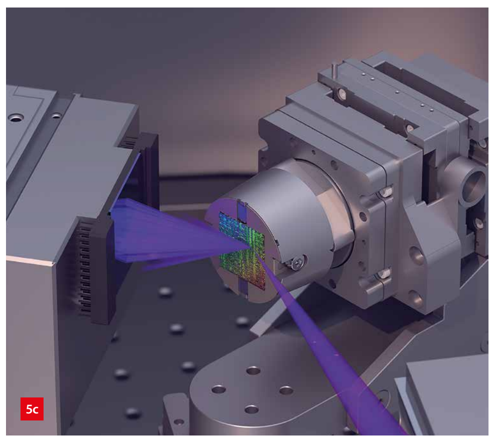
This article presents the creation of a high-resolution imaging beamline using coherent EUV light in Delft, allowing for non-destructive imaging with a high resolution. With an achieved resolution of about 100 nm, close to the expected limit in the current system settings, great potential for future computational imaging applications has been demonstrated.

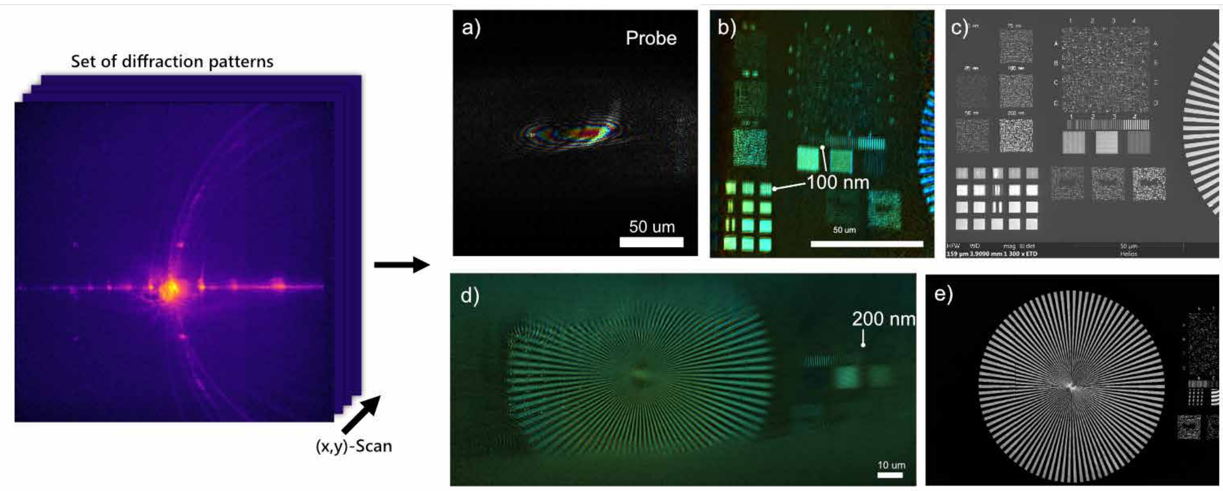
Future improvements of alignment of the ellipsoidal mirror should drastically improve the resolution, possibly down to wavelength scales. Additionally, adding a-priori knowledge could help to go even beyond those scales and move to 3D imaging.





Overview of the table-top EUV SXR beamline with a lensless microscope as the end-station. The entire system fits on a 5-m optical table.
(a) Schematic.
(b) Lab set-up.
(c) Close-up of the sample stage.





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A set of diffraction patterns is acquired and a complex probe a) and object b) can be reconstructed using the algorithm. The rather large, aberrated probe indicates that further alignment and optimisation needs to be performed.
The first reconstruction b) was able to retrieve linear gratings, with a 100 nm pitch. SEM image c) of the sample presents a reference. Another scan d) focused onto a Siemens Star (spoke target), with SEM image e) as a reference.
Note that in a), b) and d), the intensity and the colour represent the reflectivity and the phase, respectively.

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