Table-Top EUV and Soft X-Ray Microscopy

Investigating Thin Film Nanostructures and Particles

In this contribution **table-top, lab-based microscopes in the extreme ultraviolet** (EUV) in transmission and reflection mode as well as in the **soft x-ray** will be presented. The application for the transmission microscope is the investigation of **thin film nanostructures** and **particles**, the application of the reflection microscope is mask blank inspection for **EUV lithography**. The **soft x-ray water window microscope** has been developed for investigations of organic samples and nanocrystals in liquids.

Since the invention of the first optical microscope applications, microscopy has rapidly developed. The optical resolution limit as determined by Lord Rayleigh shows that the only way to improve the resolution after the maximal possible numerical aperture is reached, is to reduce the working wavelength. Thus, the constant striving for higher resolution leads to continuous decrease of the working wavelength of microscopes from visible light to UV, DUV and then to extreme ultraviolet (EUV) and X-ray spectral regions. Established first at synchrotrons, such short-wavelength microscopes are now being investigated actively with laboratory radiation sources in Aachen. Over the past decade several high-resolution microscopes were built for different industrially relevant applications. In this contribution a transmission microscope for 13.5 nm working wavelength (fig. 1), a reflection dark field microscope for 13.5 nm (fig. 2), a water window microscope for 2.88 nm (fig. 3) are presented and discussed in detail.

**EUV Transmission Microscope**

Light at a EUV wavelength provides high spatial resolution, but its penetration depth of around 100 nm makes transmission microscopy possible only for thin free-standing objects, similar to transmission electron microscopy. By utilizing specific absorption edges of single elements and multi-wavelength operation, it may be possible to obtain images with specific elemental contrast. For the investigation of thin nanostructured films or particles a laboratory-based EUV transmission microscope has been developed (fig. 1).
The EUV light of a xenon gas discharge produced plasma source is focused onto the sample by a grazing incidence ellipsoidal collector. In bright field mode the transmitted light distribution of the sample is imaged by a Schwarzschild objective to a CCD camera. Alternatively, in dark-field mode the direct transmitted beam can be blocked by an aperture stop. Light, scattered at structures or particles into larger solid angles, is collected with the objective and focused onto the CCD. As the spatial resolution of this configuration is detector pixel size limited to only 650 nm in the object plane, a second magnification step was realized, which is a transmission zone plate lens. This zone plate can be inserted into the beam path between objective and CCD camera and increases the spatial resolution to around 100 nm [1].

To proof the principle operation, a transmission test mask has been used as a sample, which contains programmed structures down to 100 nm. Additionally, Polystyrene-latex nanospheres of 112 nm diameter have been investigated. Both structures could be resolved in bright and dark field mode. Ray-tracing simulations of the microscope verified the experimental results.

**EUV Reflection Microscope**

Multilayer Bragg mirrors are efficient reflectors at EUV wavelengths and comprise the bulk of near-normal incidence angle optics at this wavelength range. For example the mirrors and masks in the upcoming EUV lithography are using Mo/Si multilayers with challenging demands on the number of present defects, both on the surface and inside the multilayer. The fast detection of such defects with sizes down to 20 nm over large mask areas is a demanding metrology task that can be solved with a EUV reflection microscope operating in dark field mode (fig. 2). In the system the EUV light of a xenon gas discharge produced plasma source is focused by a grazing incidence ellipsoidal collector via a deflection mirror onto the reflective mask blank. The reflected beam is blocked and only scattered light from defects is collected by a Schwarzschild objective, which images the defect onto a
Compared to the EUV transmission microscope, which is designed to resolve structures in the sample plane, the EUV reflection microscope is designed to have a large field of view of around 650 µm at a moderate resolution of around 1 µm. A large field of view is crucial for the required scan speed of mask blank inspection. In dark field mode a small defect, e.g. of a size of 50 nm, can only be localized within 1 µm but gives still enough signal to be detected within this area. The limitation of defect detection is given by the signal to noise ratio of the CCD camera, whereby the noise is governed by the light scattering of the multilayer mirror roughness, which produces a relatively high offset light level in the image plane.

For proof of principle operation, programmed pit defects have been written with focused ion beam into a multilayer mirror and bump defects coated onto a multilayer mirror. Both types of programmed defects have been investigated with the reflection microscope and atomic force microscope (AFM) for comparison [3]. The sizes of smallest programmed pit defects were determined by AFM to be around 80 nm, the bump defects minimal sizes were 250 nm. In the reflection microscope all defects could be successfully detected. The investigations on the ultimate detection limit of the setup are ongoing.

**Water Window Microscope**

For the investigation of nanoparticles in liquid media or biological objects in humid environment, a water window microscope has been developed [4]. In the so-called "water window" between 2.3 nm and 4.4 nm water is transparent, compared to carbon, cadmium or lead, which gives an excellent contrast for microscopy. For this setup a high input power plasma soft X-ray source was built to produce radiation from a highly ionized nitrogen plasma with a wavelength of 2.88 nm. The light was then focused by a grazing incidence collector to the sample under investigation. A titanium filter between collector and sample blocks light with higher energies, to reduce the total irradiation level at the sample and to improve the contrast of the image. The transmitted light from the sample is imaged by a zone plate objective to a CCD camera. The zone plate has an outermost zone width of 30 nm, which determines the spatial resolution of the microscope to around 40 nm.

To proof the principle operation diatoms and latex spheres have been investigated. Over a large field of view of around 20 µm detailed structures of diatoms and latex spheres could be observed and resolved.
Straightforward extension of the method to tomographic 3D imaging of samples is currently under implementation.

**Conclusion**
In this contribution latest developments in the EUV and soft x-ray microscopy have been presented. Short-wavelength imaging can be successfully realized with compact laboratory footprint independent of synchrotron facilities. This enables rapid commercialization of the EUV and soft X-ray based developed metrology tools.

**References**

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