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Invited Paper

EUV Imaging of Nanostructures without Lenses

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ABSTRACT

Next-generation metrology solutions in various technology areas require to image sample areas at the nanoscale. Coherent diffractive imaging based on ptychography is the route towards EUV imaging of nanostructures without lenses. A key component in a table-top EUV beamline is a high-brightness high-harmonic generation (HHG) source. Since our research is mainly directed towards wafer metrology for lithography in the semiconductor industry, we adhere to a reflection set-up: the EUV light is scattered by the nanostructures at the surface of the sample, and is reflected towards a CCD camera, where a far-field diffraction pattern is recorded. A data-set comprising a multitude of these diffraction patterns is generated for partially overlapping positions of the focused probe on the sample. This provides the necessary redundancy for phase retrieval of the complex-valued field of the sample. Recent advancements in both hardware and software for computation enable the development of advanced algorithms. In particular, the benefits of automatic differentiation are exploited in order to cope with a drastic growth in model complexity. Our computational imaging algorithms realize wavelength-multiplexed reconstruction and a modal approach for the spatial coherence of the source.

Keywords: ptychography, computational imaging, EUV metrology, phase retrieval, automatic differentiation.

1. INTRODUCTION

Our EUV beamline is built around a compact HHG source, which is pumped by a Yb-doped fibre laser at 1030 nm. This IR laser has an average power of 100 W at a repetition rate of 600 kHz. The IR pulses of 300 fs are further compressed to 28 fs by an hollow core fibre, which yields 68 W average power at its output. The IR beam is focused into a 10-bar pressurized Argon gas jet, as shown in Fig. 1. This enables the generation of higher harmonics in the soft X-ray and EUV regimes. The strongest EUV harmonic is obtained at 68 eV (λ=18 nm) with a flux of 2 10^{11} photons/sec at the gas jet [1].

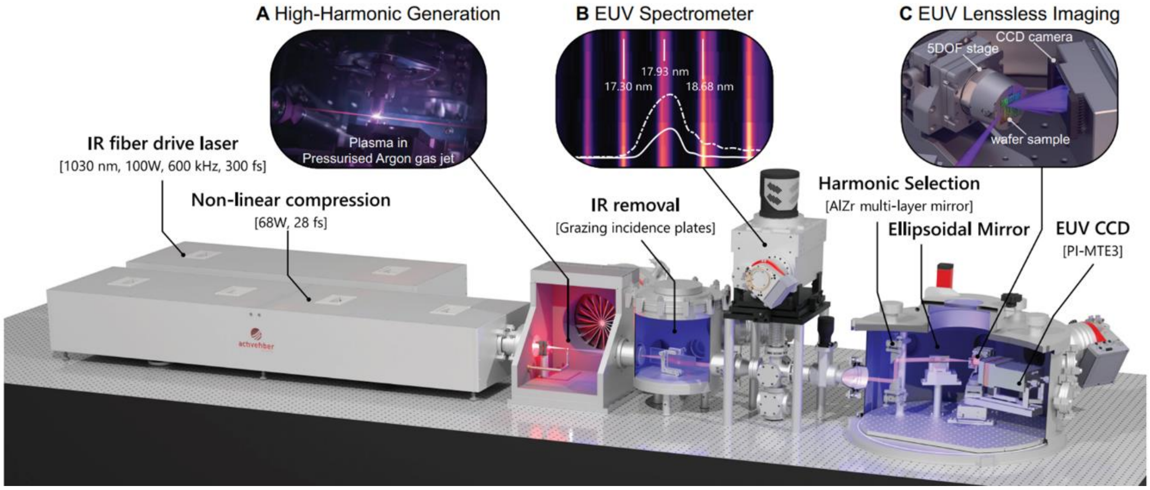

Fig. 1. EUV Beamline with: (A) HHG EUV-source; (B) EUV Spectrometer; (C) EUV Chamber for Lensless Imaging.

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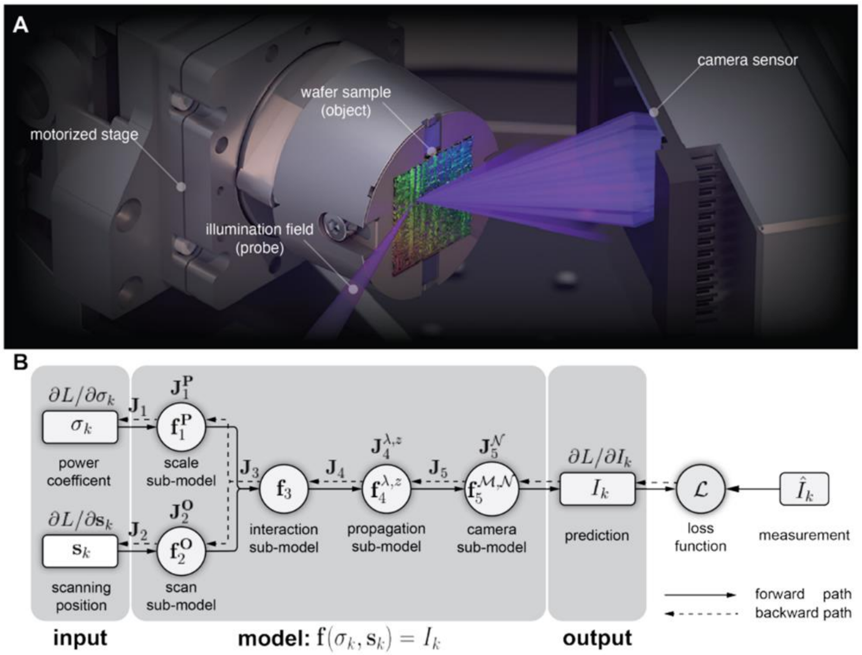

Fig. 2. The ptychography process and the computational graph for the reconstruction.
(A) Reflection geometry at our EUV beamline. (B): The computational graph with the concatenation of sub-models for the reconstruction. f and J denote the function and the corresponding Jacobian of each sub-model.

Fig. 2 shows the algorithmic approach for the optimization-based ptychographic reconstruction as devised in [2]. The overall model is built as a concatenation of various sub-models. Each of these sub-models is represented by a specific function denoted by f, which is differentiable with respect to its input parameters. With the concept of automatic differentiation (AD), computing the gradients of all variables becomes one unified process. AD essentially applies the chain rule to the overall composite function f and accumulates the Jacobians (matrices of partial derivatives) at all nodes when traversing the computational graph from the loss function at the output to input during a reverse pass.

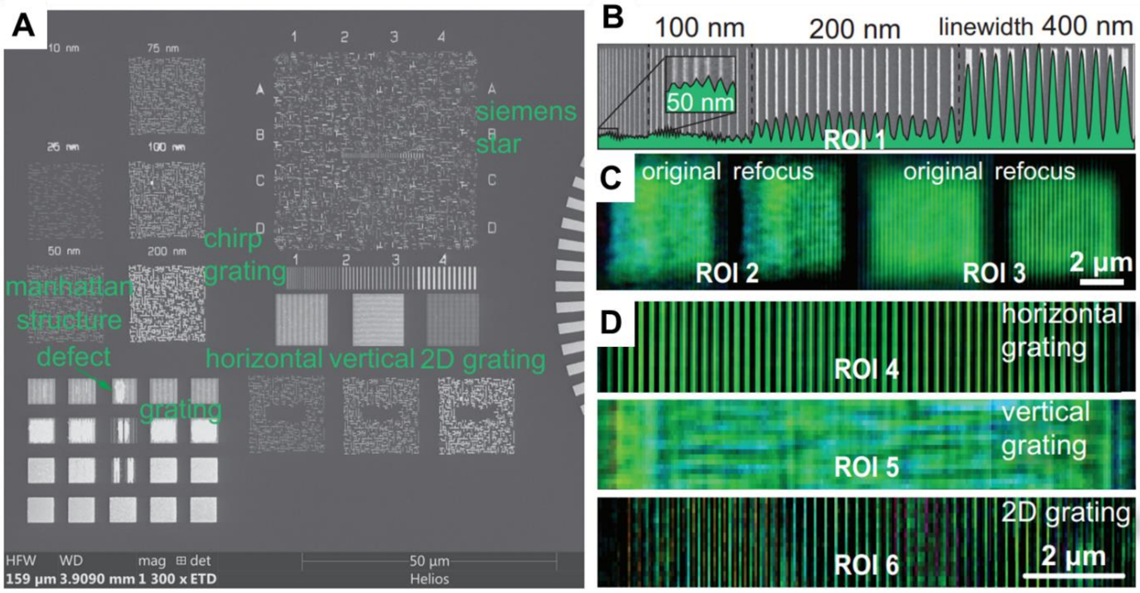

Fig. 3. (A): SEM-image of the sample. (B): Profile of the chirped grating with 200 nm, 100 nm, and 50 nm lines with varying spacing. Inset: the finest part of the chirped grating with 50 nm lines. (C): Gratings in squared areas (with a defect), before and after digital refocusing. (D): Reconstructed structures in horizontal, vertical and 2D gratings.

2. RESULTS

In Fig. 3, a number of ptychographic reconstructions are shown for various types of small-sized grating structures, that is, with (a) chirped gratings, (b) 1D horizontal and (c) 1D vertical gratings, and (d) 2D gratings. The chirped gratings reveal a resolution down to 50 nm. Because our reflection geometry uses a large tilt angle of 70^o (w.r.t. the surface normal), the probe is quite elongated in one direction. This results in a non-uniform resolution, so that only the horizontal grating and the horizontal part of the 2D grating can be resolved. Fig. 4 shows the inference of the height of patterned Au structures on top of a Si substrate as derived from the reconstructed phase of a Siemens star. The retrieved height of about 20 nm is in close agreement with AFM measurements. Note that the height is computed using the ptychographic phase difference from Fig. 4(B), the incident angle, the wavelength, and the prior knowledge of the optical properties (refractive index and absorption coefficient) of the constituent materials by means of the Fresnel relations.

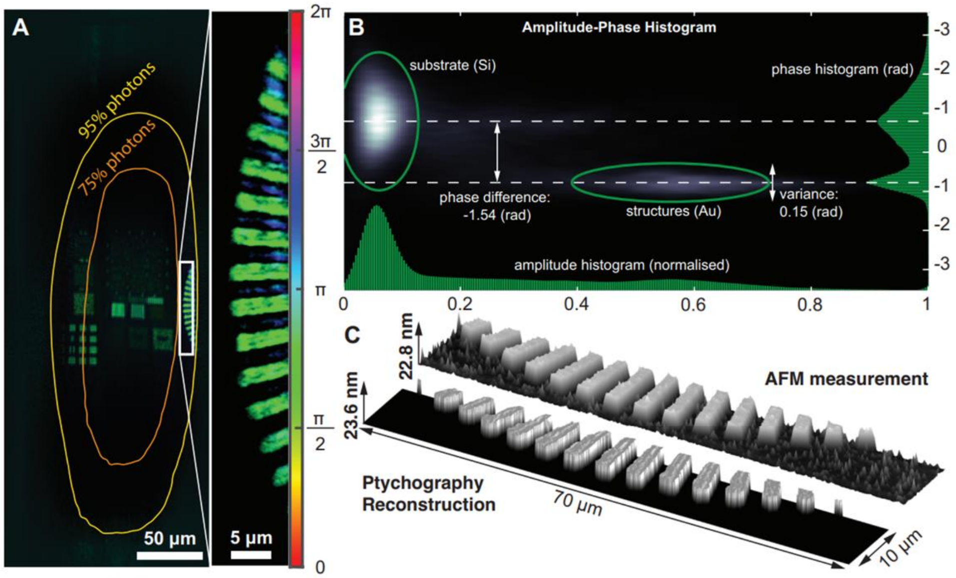

Fig. 4. 3D structure information characterization. (A): The field-of-view of the reconstructed object. The ellipsoidal contours mark the areas illuminated with 75% and 95% of the total flux. Inset: edge of the Siemens star. (B): Distribution of pixel values in amplitude and phase. (C): 3D views of the AFM measurement and the ptychographic reconstruction. The height is computed using the phase difference from (B), incident angle, wavelength, and material properties.

3. CONCLUSION

The ptychographic reconstruction of various samples in a reflection geometry at EUV wavelengths highlights the ability of ptychography as an efficient and accurate metrology tool for the structural analysis of nanostructures. The following achievements and observations are briefly summarized here:

- A non-isotropic resolution results as a characteristic feature for ptychography in a reflection geometry with a typical large tilt angle between probe and sample.
- An in-plane resolution of 50 nm has been realized for a wavelength of 18 nm for a reflection geometry with a tilt angle of 70^o (w.r.t. the normal to the sample plane) along the direction orthogonal to the tilt axis.
- Inference of topological height information has been realized via use of the phase as retrieved through ptychography in case of structures in a Au layer with a thickness of about 20nm, residing on top of a Si substrate.
- Last but not least, the recently introduced universal ptychography algorithm of [2] based on the automatic differentiation (AD) framework has been demonstrated to be a powerful tool for EUV diffractive imaging. It can deal with a highly complex model comprising a number of concatenated differentiable sub-models, which enables to perform multi-wavelength ptychographic reconstruction, to cope with source instabilities and to deal with numerous sources of experimental uncertainties like offsets in positions of the scanning probe along the ptychographic scan.

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