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Multi-Modal Extreme-Ultraviolet Reflectometer: Solving Inverse Problems in Nanoscale Metrology

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Abstract: We present a unique instrument, designed to characterize the composition, geometry, topography, and interface quality of 2D heterostructures. We demonstrate three modes of characterizations, including reflectometry, scatterometry, and coherent diffractive imaging reflectometry.

1. Introduction

Modern semiconductors as well as photonic, energy and quantum devices can benefit tremendously from characterization techniques that have high spatial resolution, are non-destructive, and comprehensive enough to capture the relevant parameters of a sample [1]. Here we present a tabletop EUV imaging reflectometer for high-fidelity metrology of nanostructures. It has three measurement modes: intensity reflectometry, scatterometry, and coherent diffractive imaging reflectometry. By solving the inverse problem from the collected EUV diffracted light, we extract sample parameters with elemental specificity and high transverse and axial spatial resolution [2-4].

2. Intensity Reflectometry

The first mode of characterization is intensity reflectometry, where we measure the specular reflectivity of the EUV beam illuminating the sample as a function of incidence angle to solve for multi-layered composition, thicknesses, and interface quality. The measurement is aided by normalization of the incident intensity via a beam splitter. The collected data is used to solve the inverse problem by fitting synthetic diffraction data simulated with a Parratt-formalism based reflectivity calculator [2]. Optimization of the fit is performed via a genetic algorithm. The collected data and resulting fit are shown in Figure 1 [3].

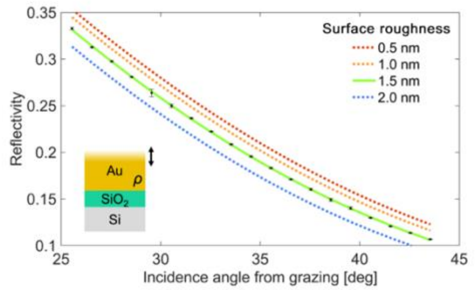

Figure 1 **Intensity reflectometry on a 100 nm Au thin film on Si**. The measured reflectivity (black data points) and the theoretical solution fit (solid light green). Additional theoretical curves with varied surface roughness are also shown in dotted lines. Insets: cross-sectional sample schematic and solved parameters (surface roughness and density of the Au layer).

3. Scatterometry

The second mode we demonstrate is scatterometry, where we measure the diffraction efficiencies at some or many diffracted orders as functions of the incidence angle. We measured Ni line gratings with a nominal 100 nm linewidth, 400 nm period, and 12.9 nm height patterned using electron lithography on a polished sapphire substrate. As shown in Figure 2, detailed material parameters such as line edge roughness as well as some unexpected features were extracted by solving for the inverse problem related to the diffraction efficiencies.

4. Coherent Diffractive Imaging Reflectometry

The third mode is coherent diffractive imaging reflectometry, where quantitative imaging of the sample's complex reflectivity is achieved through ptychography and subsequent device parameters are extracted using reflectometry.

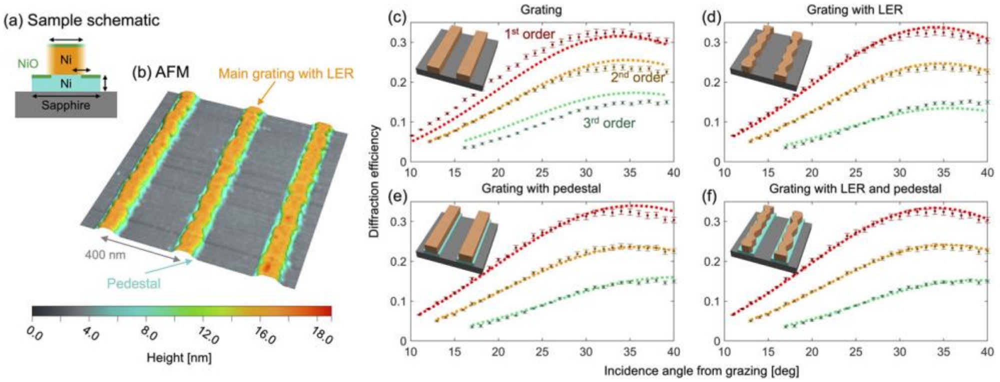

Figure 2 **Scatter-reflectometry on Ni line gratings on a sapphire substrate.** (a) Cross-sectional sample schematic and solved parameters. (b) AFM image of the sample. (c–f) 1st, 2nd, and 3rd order EUV diffraction efficiency as a function of the incidence angle, and best fits obtained for: (b) simple rectangular grating; (c) grating with line edge roughness (LER); (d) grating with pedestal; and (e) grating with LER and pedestal.

We demonstrated imaging reflectometry on a calibrated AFM test sample from BudgetSensors (CS-20NG-UM) that contains SiO_2 structures on a Si substrate with native oxide growth. We achieve high-resolution, complex imaging by the use of coherent diffractive imaging which numerically reconstructs the phase information in collected diffraction patterns. We utilize a particular form of CDI called ptychography that can robustly converge resulting in quantitative amplitude and phase images. By imaging the sample at multiple angles of incidence, we were able to extract both the amplitude and phase information of the sample with good spatial resolution within an extended field of view. The same reflectometry technique provided us with sample parameters such as the thickness of substrate passive SiO_2, and the height of the SiO_2 structures (see Figure 3) [2].

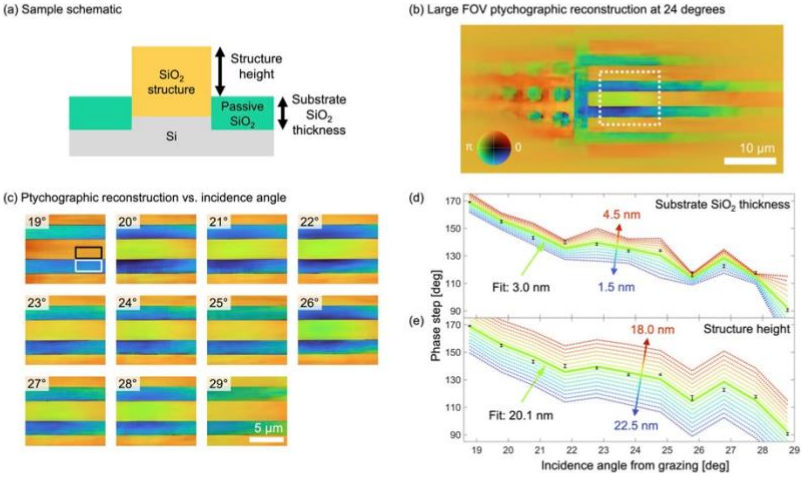

Figure 3 **Imaging reflectometry of SiO_2 structures on a Si substrate.** (a) Sample schematic and the two measured parameters. (b) Ptychographic reconstruction of the sample at 24 degrees from grazing, where brightness corresponds to the amplitude and the hue to the phase. The white dotted rectangle indicates the cropped region for (c) and corresponds roughly to the area covered by the $1/e^2$ extent of the probe. (c) Center area of the ptychographic reconstructions taken at 11 incidence angles. Black and white rectangles shown in the 19-degree reconstruction indicate the pixels used in regions on the structure and the substrate respectively to calculate the phase-step curve. (d–e) The measured phase step between the structure and the substrate (black data points), and the theoretical solution fit (solid light green).

5. References

[1] G. Orji, B. Bunday, and Y. Obeng, International Roadmap for Devices and Systems: Metrology (IEEE, 2022).

[2] Y. Esashi *et al.*, “Influence of surface and interface roughness on X-ray and extreme ultraviolet reflectance: A comparative numerical study,” *OSA Continuum*, vol. 4, issue. 5, p. 1497-1518, 2021, doi: 10.1364/OSAC.422924.

[3] Y. Esashi *et al.*, “Tabletop extreme ultraviolet reflectometer for quantitative nanoscale reflectometry, scatterometry, and imaging,” *Review of Scientific Instruments*, vol. 94, no. 12, p. 123705, Dec. 2023, doi: 10.1063/5.0175860.

[4] M. Tanksalvala *et al.*, “Nondestructive, high-resolution, chemically specific 3D nanostructure characterization using phase-sensitive EUV imaging reflectometry,” *Sci. Adv.*, vol. 7, no. 5, p. eabd9667, Jan. 2021, doi: 10.1126/sciadv.abd9667.

[5] N. J. Brooks *et al.*, “Temporal and spectral multiplexing for EUV multibeam ptychography with a high harmonic light source,” *Opt. Express*, vol. 30, no. 17, p. 30331, Aug. 2022, doi: 10.1364/OE.458955.