Ptychographic Phase-Sensitive Imaging Reflectometry for Depth-Resolved Nanostructure Characterization using Tabletop EUV Light

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Abstract: We present a versatile, ptychographic phase-sensitive imaging EUV reflectometer that can nondestructively image samples with spatial, depth and compositional resolution, with sensitivities to dopant levels and interface quality.

1. Introduction

Next-generation semiconductor and quantum devices will utilize intricately designed 3D heterostructures. As a result, minor defects in their structure, interfaces, or composition can significantly degrade their performance. Continued advances in the fabrication of new devices demands a parallel advance in nano-characterization techniques capable of non-destructively imaging 3D structures.

We present a unique, non-destructive, EUV imaging-reflectometer to meet these demands. Our technique utilizes coherent EUV illumination from a table-top high harmonic generation (HHG) source, that enables imaging with high transverse and axial spatial resolution with the ability to penetrate materials that are opaque to visible light [1-3]. Our phase-sensitive imaging reflectometer uses ptychographic imaging at multiple grazing-incidence angles to produce angle-resolved, high-resolution, amplitude and phase images with sensitivity to elemental composition, topography and interfaces. These contrast mechanisms allow us to determine a high-resolution 3D map of material composition. The microscope we developed can use 13 or 30 nm illumination at a controllable, near-grazing incidence angle to ensure high reflectivity for almost all materials and thus provide a general-use imaging technique.

2. Results

As a first demonstration, we imaged a semiconductor sample using ptychographic imaging at incidence angles of 21-25 degrees, where our microscope was illuminated by coherent high harmonic beams at a wavelength of 30 nm (Fig. 1a). Ptychography is a powerful lensless computational imaging technique that has unique advantages in the EUV and soft X-ray regions because of its ability to quantitatively image samples with phase-sensitivity, at a resolution smaller than the illumination spot size, and with robustness to noise [4-6]. Each ptychographic image of the sample was spatially segmented to determine the phase steps between different regions of the sample as a function of the incident angle. The angle-dependent phase step, along with a parameterized model of the sample was then used in a genetic algorithm to solve for the depth-dependent chemical composition of the sample. The solved-for parameters are in good agreement with correlative metrologies, including secondary ion mass spectrometry (SIMS), atomic force microscopy (AFM) and transmission electron microscopy (TEM)-based imaging techniques.

The sample consisted of Si_3N_4/SiO_2 structures on top of a Si substrate, with varying levels of As dopant in the substrate patterned independently of the structures (Fig. 1b). This was a challenging sample to image, due to its low reflectivity and contrast, high periodicity, and multiscale features. However, we achieved a high-fidelity image (from incidence angle of 30 deg, shown in Fig. 1c). Required for this high fidelity was an HHG source extremely stable in both pointing and power, precise correction for the exact 3D rotation of the sample, and other regularizations incorporated into the ptychographic reconstruction algorithm including total variation [7] and Fourier soft thresholding.

The parametric model of the sample solved from the phase steps, combined with the high-fidelity reconstruction into a 3D rendering is shown in Fig. 1c. Strong elemental contrast at EUV wavelengths allows for us to solve for the depth-resolved chemical composition in the sample (shown as different color coding for different materials), including layer thicknesses, dopant levels and interface quality. Notably, our technique is spatially resolved in contrast to most ellipsometry and scatterometry techniques, and it is non-destructive - unlike transmission electron microscopy and secondary-ion mass spectroscopy.

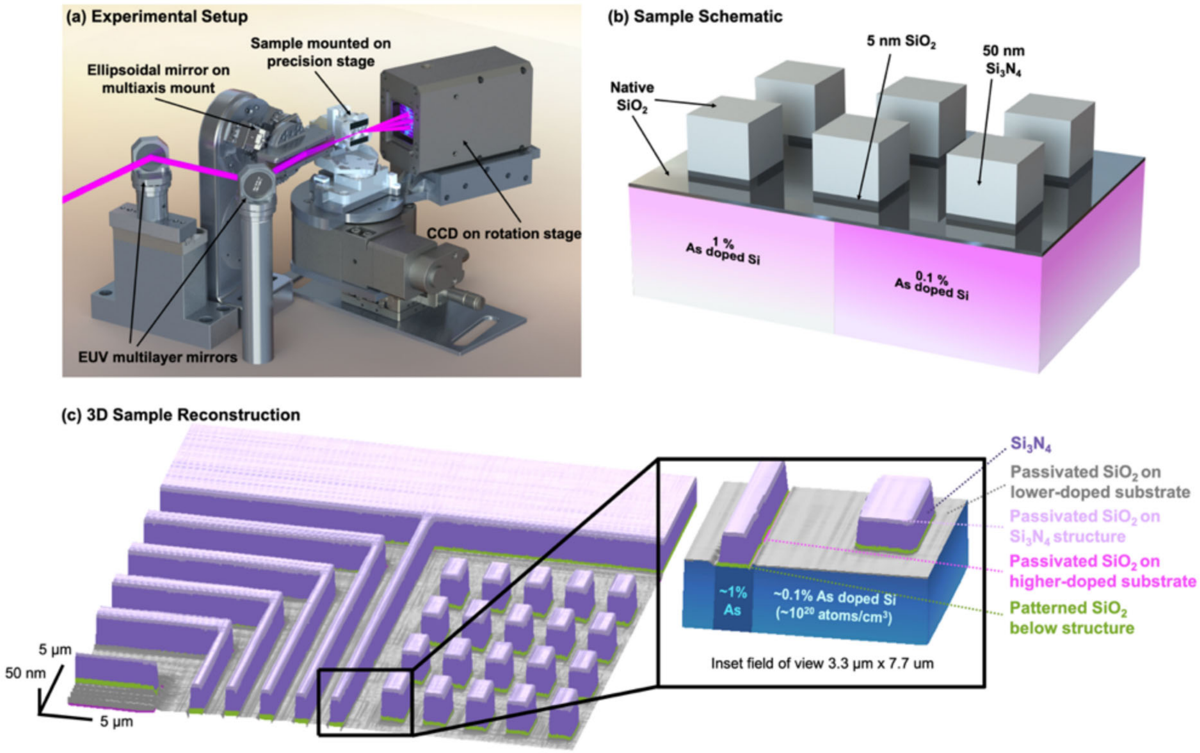

Fig. 1. Experimental setup, sample schematic, and imaging results. (a) Experimental setup of EUV imaging reflectometer. The precision sample stage and camera rotation arm allow for the precise collection of the reflected EUV scatter at multiple angles. (b) Design schematic of the sample showing nominal structure heights and layer thicknesses. (c) 3D rendering of the reconstruction at 30 degrees incidence angle, where different materials are color-coded. The inset shows a region of the reconstruction similar to the design schematic.

3. Conclusion

We have developed a versatile and tabletop EUV coherent diffractive imaging microscope that images objects at multiple angles of incidence. This allows us to robustly solve for spatially resolved, depth-dependent chemical composition of nanostructures. By utilizing the strengths of using EUV light at grazing incidence, this microscope is sensitive to thin film structures and dopant levels. This is a significant advancement for tabletop EUV imaging and has many exciting scientific and industrial applications — particularly in assisting the development and implementation of next-generation quantum, semiconductor, and spintronic devices.

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5. References

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