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High-resolution, Data-driven 3D X-ray Imaging of Microchips using Ptychography

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Abstract. As transistor dimensions have shrunk over the years, X-ray microscopy resolution has also improved to meet the demands of the semiconductor industry. Although electron microscopy can achieve higher resolution, X-rays offer unique advantages, including non-destructive 3D imaging of fully intact integrated circuit dies and the future possibility of imaging under operando conditions. In this work, we demonstrate the capabilities of ptychographic X-ray computed tomography for 3D microchip imaging at 4 nm resolution. To achieve such performance, we introduce newly developed methods to overcome nm-scale experimental instabilities and depth-of-field limitations. Microchip-specific high-throughput data collection methods will also be introduced.

1 Introduction

As ptychographic X-ray tomography [1] approaches single-digit or sub-1 nm 3D imaging resolution, it is the ideal candidate to bridge the resolution gap between transmission electron microscopy (TEM) and X-ray microscopy. This leap towards finer resolutions, however, introduces critical challenges: the depth-of-field dramatically narrows due to a square-law dependence [2], and the imaging process becomes increasingly susceptible to nanometer-sized instabilities. Therefore, imaging larger samples at high resolution requires new approaches in both image acquisition and reconstruction to expand the depth-of-field and correct for experimental errors. By addressing these challenges, X-ray nano-tomography can not only push the boundaries of resolution but also circumvent the intricate sample preparation required by TEM, while leveraging the high penetration

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depth of X-rays. This advancement would enable imaging of large samples necessary for connectome mapping of integrated circuits or brain samples, opening new frontiers in high-resolution X-ray tomography.

2 Burst ptychography and extended depth of field tomography

To address these challenges, we introduced two novel methods aimed at mitigating X-ray beam instabilities and extending depth-of-field limitations beyond current capabilities. Our first approach, "burst ptychography", involves capturing multiple low-exposure frames at each scan position to better resolve temporal dynamics of instabilities. This method simplifies the reconstruction process by reducing algorithmic complexity, compared to mixed-state ptychography [3] which relies on inferring dynamics from a single image. Our second approach uses a filtered back-propagation tomography algorithm from optical diffraction tomography [4] to image samples larger than the depth-of-field. Our experimental results demonstrate this method's ability to extend the depth-of-field by at least tenfold without requiring multi-slice approaches [5], even for strongly scattering samples such as integrated circuits.

3 Data-driven tomography of microchips

While high-resolution 3D imaging is crucial for semiconductor metrology using X-rays, such imaging methods lack the necessary throughput for large-scale microchip inspection. One way to extend the imaging throughput is by exploiting the anisotropic structure of the microchips, which is a consequence of the lithographic manufacturing process. We will introduce new data acquisition strategies which can leverage the anisotropic microchip structure to increase the data acquisition speeds while also lowering the X-ray dose and minimizing the radiation induced damage. Also, we will demonstrate how the acquisition parameters for each ptychographic projection can be adjusted to yield optimal reconstruction quality at every sample rotation angle.

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