doi:10.1017/S1431927618012576
Microsc. Microanal. 24 (Suppl 2), 2018

High-Resolution and High-Throughput Ptychography with Depth Sensitivity Using Multilayer Laue Lenses

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As the depth-of-focus imposed by the optics or the depth-of-field imposed by the detector shrink consistently with the finer spatial resolution, the sample thickness is usually required to be thin enough for high-resolution imaging. This limitation hinders obtaining high quality images from thick samples or specimen embedded inside in-situ cells. The multi-slice concept was proposed to model the multi-scattering effect inside a thick sample by decomposing it into a series of layers, where each layer is thin enough to satisfy the projection approximation with adjacent layers related by a wavefront propagation. The exitwave from the sample carries the depth information, which can be used to reconstruct the images on all layers, and thus this approach is able to extend the depth-of-field without sacrificing resolution [1].

Applying the multi-slice ptychography method in X-ray regime is challenging, because the depth resolving capability is provided either by the depth of focus of the X-ray optics with large numerical apertures, or by the depth of field defined by the recorded high-q scattering signal which decays dramatically against the spatial frequency. To obtain high lateral spatial resolution and desired depth resolution, it usually requires 10s of seconds dwell time per scan point to collect high-q signal with sufficient signal-to-noise ratio [2,3,4], which significantly limits the throughput of this method. We propose to solve this problem by using the highly convergent X-ray beam focused by multilayer Laue lens with large numerical aperture. The narrow depth-of-focus helps enhancing the depth resolution, while the bright holographic region provides intense diffraction signal for about 10 nm resolution with a significantly reduced exposure time. To further increase the throughput of the method, the ptychography scan was conducted in the on-the-fly scan mode to eliminate the scan overhead. The synergy of multi-slice ptychography with multilayer Laue lens and on-the-fly scan mode provides a powerful tool to achieve high spatial resolution and moderate depth resolution with significantly improved throughput. This approach can be adopted by other types of high NA optics, such as zone plates and KB mirrors.

The 12 keV X-ray probe used in this work was focused by a crossed pair of MLLs, as shown in Fig. 1(a). Before the multi-slice measurement, the probe wavefront was characterized by a ptychographic reconstruction. The beam size at the focal plane is 12×12 nm, which represents the point-spread-function of our imaging system and suggests a 12 nm resolution as the baseline of the scanning probe microscope. The sample is a silicon wafer with 10 μm thickness. We prepared gold nano-particles on its front surface and nickel oxide particles on its rear surface. As the separation of these two particle planes exceeded the depth-of-focus of the MLLs used in the experiment (4 μm), the conventional ptychography reconstruction is not able to provide an image with sharp features of both particles [5]. The sample was placed 20 μm downstream of the focal plane to enlarge the beam size and improve the overlapping condition [6]. The multi-slice measurement was performed in the on-the-fly scan scheme covering 1.2×1.2 μm range with 20 nm step size and 0.05 second dwell time per point. The far-field diffraction pattern was collected by a Merlin detector placed 0.5 m away from the sample. The averaged photon counts inside the holographic area is above 1000 with 0.05 exposure time, which gives sufficiently high signal-to-noise ratio for the faithful reconstruction.

Using the multi-slice ptychography reconstruction engine, two separated planes were reconstructed successfully [7]. The particle features agree very well with the simultaneously measured fluorescence maps, as shown in Fig. 1(b). The spatial resolution in the lateral plane was estimated using phase retrieval transfer function and Fourier shell correlation methods, which give 8.1 nm and 9.2 nm, respectively. To accommodate the blurry effect introduced by continuous motion, five illumination modes were included in the multi-slice reconstruction process.

In summary, sub-10 nm lateral resolution and 10 μm depth resolution were achieved with 0.05 second dwell time by using focused beam from MLLs with large numerical aperture. The significantly increased throughput rate allows this approach as a realistic tool for high-resolution three-dimensional imaging of thick samples.

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[8] The authors acknowledge the Laboratory Directed Research and Development (LDRD-21690) program. This research used resources of the National Synchrotron Light Source II, a U.S. Department of Energy (DOE) Office of Science User Facility operated for the DOE Office of Science by Brookhaven National Laboratory under Contract No. DE-SC0012704.

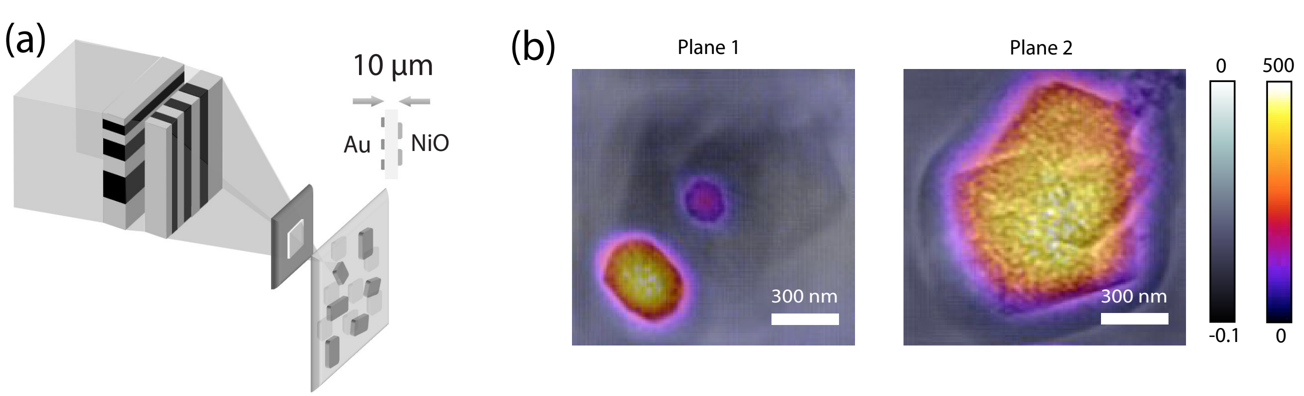

Figure 1. (a) Experimental setup for the multi-slice ptychography experiment with MLLs. (b) The reconstructed phase images of nano-particles on two separated planes, overlaid with the fluorescence maps.

https://doi.org/10.1017/S1431927618012576 Published online by Cambridge University Press