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# High-speed Three-dimensional Imaging at the Nanoscale via Fly-scan Ptycho-tomography

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Ptychography has revolutionized coherent X-ray microscopy and became a mainstream technique for high-resolution imaging. Combined with conventional methods such as tomography and laminography, the technique has been successfully extended to 3D imaging, with state-of-the-art beamlines reaching below 20 nm spatial resolution [1,2], further providing new opportunities for characterizing materials such as integrated circuits (IC) and biological specimens. Moreover, the scanning sample scheme allows ptychography to be easily scaled to large objects at millimeter and even centimeter-scale.

With fourth-generation synchrotron sources on the horizon, there is a growing interest in developing fly-scan ptychography [3,4,5], where the sample is moved continuously as diffraction patterns are recorded to take advantage of the increase in coherent flux. By eliminating the overhead for stage acceleration, deceleration and stabilization, the fly-scan scheme enables ultra-fast and more efficient data acquisition. Developed at the Advanced Photon Source, the Velociprobe instrument is dedicated to fly-scan ptychography and routinely used for high-resolution and large field-of-view imaging. As shown in Figure 1, with double-multilayer monochromator and advanced maximum likelihood reconstruction algorithm [6], the Velociprobe instrument can image an IC at 10 nm resolution using diffraction patterns acquired at maximum detector rates of 3000 Hz, which is equivalent to an imaging rate of 9 x $10^4$ resolution elements per second [7].

Recently, the Velociprobe instrument was upgraded with a stable air-bearing rotation stage that provided additional tomography capability. Figure 2 shows 3D reconstructions of a CuS secondary particles – an important multifunctional semiconductor with potential applications in gas sensors, lithium ion batteries and solar energy devices. In the fly-scan mode, each projection with a 30 x 15 $\mu m^2$ field-of-view was measured at 500 Hz frame rate, and more than 300 projections were acquired in less than 3 hours. After ptychographic reconstruction, the projection images were processed and aligned using a novel projection-matching technique [8] and the missing wedge in Fourier space was “filled” with total variation regularization based on the approach developed for laminography [2].

Based on the line-profile method, the 3D resolution of the tomogram is estimated to be 30 nm. With fast scanning capability, the APS is well-positioned to perform high-throughput ptycho-tomography experiments from imaging large objects to *in-situ* characterization [9].

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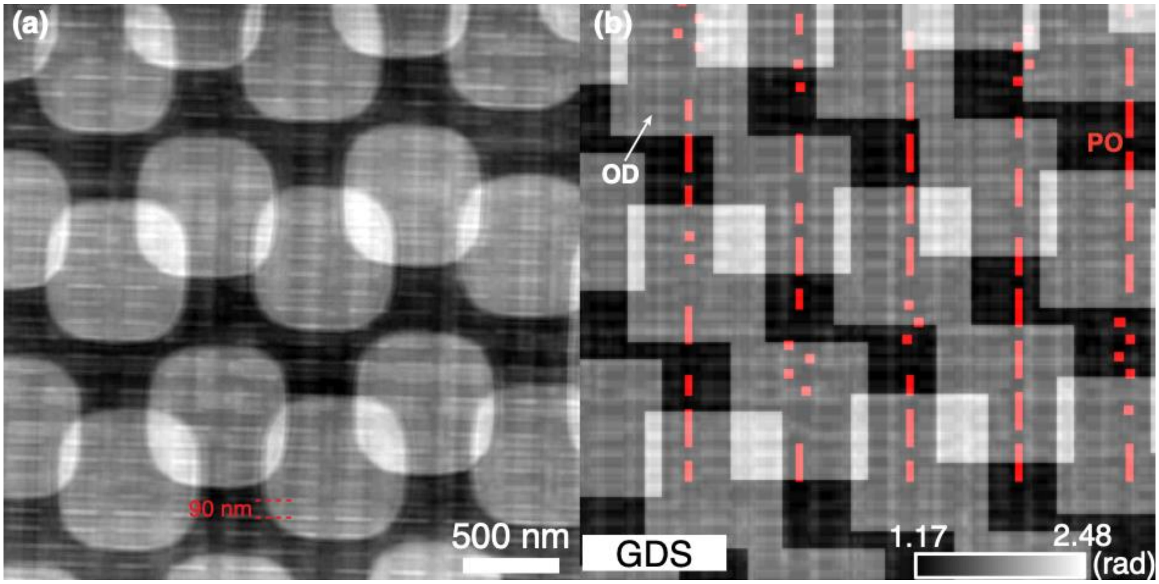


**Figure 1.** Ptychographic reconstruction of an integrated circuit measured at 3000 Hz frame rate [7]. (a) Reconstructed phase. (b) Simulated phase image calculated from the chip design files (labeled by "GDS"). The OD connections, which have 40-nm width and 90-nm spacing, in the bottom oxide diffusion layer and the PO gates are clearly resolved in the ptychographic reconstruction.

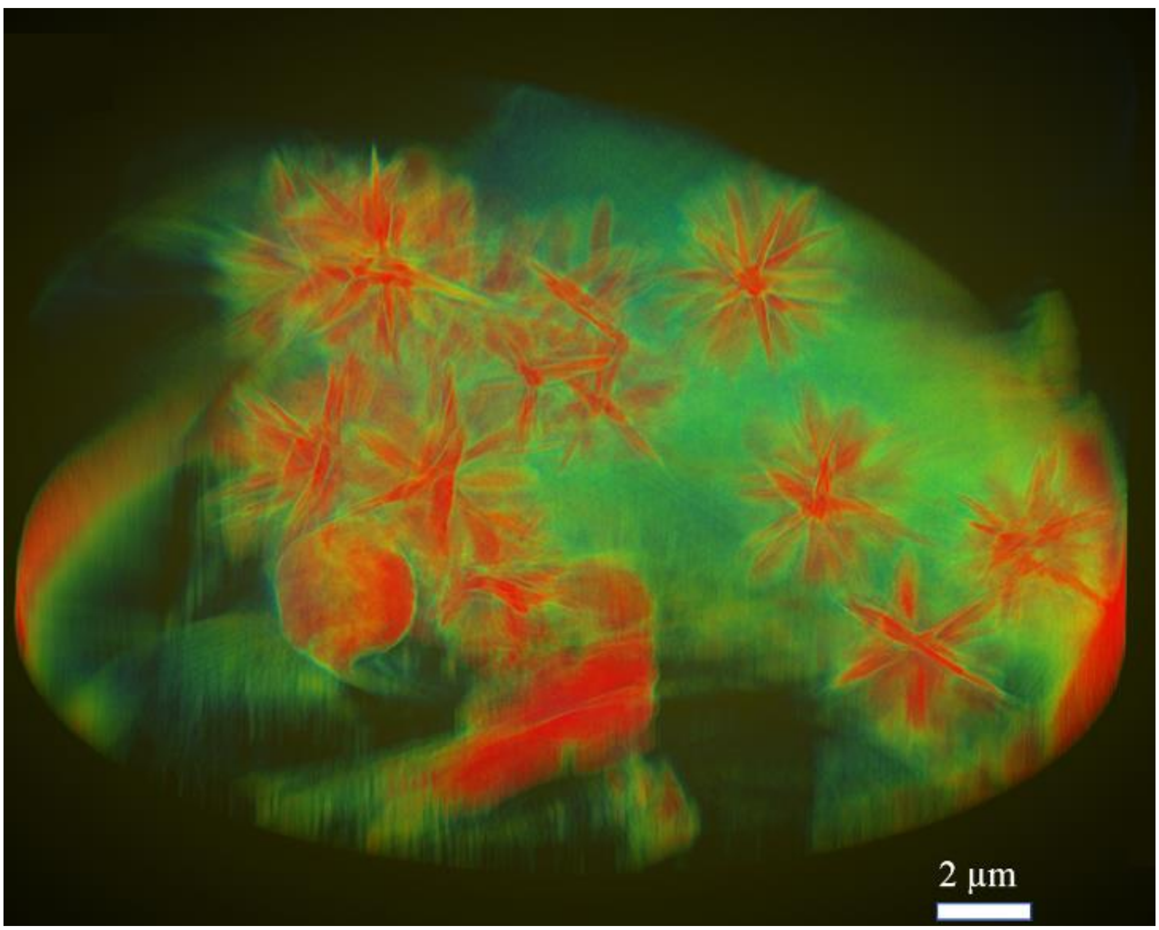

**Figure 2.** 3D rendering of CuS particles reconstructed by ptycho-tomography measurements on the Velociprobe instrument at the APS. The tomogram was reconstructed from 333 projections with a field-of-view of 30 x 15 µm2. The total data acquisition time was under 3 hours.

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