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STEM Phase Imaging by Annular Pixel Array Detector (A-PAD) Combined with Quasi-Bessel Beam

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Recent advances in STEM detectors have reached to the pixel array detectors (PADs) enabling to obtain whole information in reciprocal space during probe scanning [1]. The coauthor Ikuta also had developed a squarely arranged PAD for STEM, which consists of 8x8 detection portions [2]. One of the applications of the PAD in STEM is phase retrieval such as the ptychographic microscopy [3]. This iterative technique is capable to represent phase images, however, in which specimen thickness has to be enough thin to be as the weak phase objects. In order to overcome this restriction, we have proposed the novel STEM phase retrieval technique using annularly-shaped pixel array detector (A-PAD) combined with quasi-Bessel beam [4]. In this paper, we demonstrate applicability of our method called **P**hase **Re**trieval for **T**hick **S**pecimens (PRETS).

Figure 1 shows a schematic illustration of the proposed phase retrieval method. By using an annular aperture to form hollow-cone-shaped probe, its intensity distribution is elongated along the optical axis [4]. This means depth of focus (DOF) is extended, which is limited finitely due to the finite width of the annular slit. Such probe does not correspond to the Bessel beam providing infinite DOF, but should be called as the quasi-Bessel beam. This extended DOF results in applicability to thick specimens. The annular aperture has the other effect to restrict the distribution of the electrons going forward to the detection plane, as shown in Fig. 1. This leads to that, for bright-field (BF) imaging, the pixelated detectors are permitted to be located just at the annular-shaped region where the direct beam illuminated. This is the reason why we have developed the A-PAD system. Each detectors in the A-PAD yields BF-STEM images containing different information of specimen. From these components, the phase information can be extracted and reconstructed by a dedicated Fourier filter having an acentric annular shape and a summation of the filtered components.

Figure 2 shows the developed A-PAD apparatus. This contains 31 detectors in which 24 channels (#0-23) are used for the phase retrieval and the others for normal BF imaging, as shown in Fig. 2(a). Each channel consists of a bare optical fiber having 0.5mm in diameter, one end of which is coated directly by a scintillator made of P-47 powders (Fig. 2(b) and (c)). The other ends of the fibers are connected to a multianode photomultiplier tube (PMT). These fibers transfer the photons converted from electrons on the detectors. Eventually, output signals from the PMT are fed into an image processing computer. The detector is mounted on the x-y position adjustable stage, as shown in Fig. 2(d), which was assembled in the STEM column for the experiments.

Figure 3 shows phase maps for comparison in terms of thickness effect by means of the multi-slice simulations. The phase in the TEM corresponding to imaginary part of the exit wave is strongly affected by increment of specimen thickness, as shown in Fig. 3(b). In contrast, phase retrieved by the proposed method can represent directly atomic structures without the contrast reversal even at 15 nm in thickness. This clearly proves the effectiveness of our novel technique PRETS.

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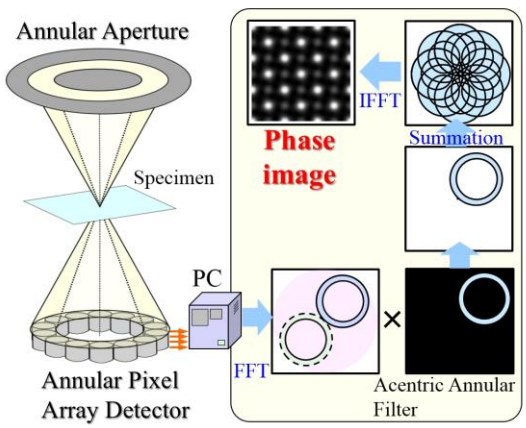

Figure 1. Schematic illustrations of a new STEM phase imaging technique.

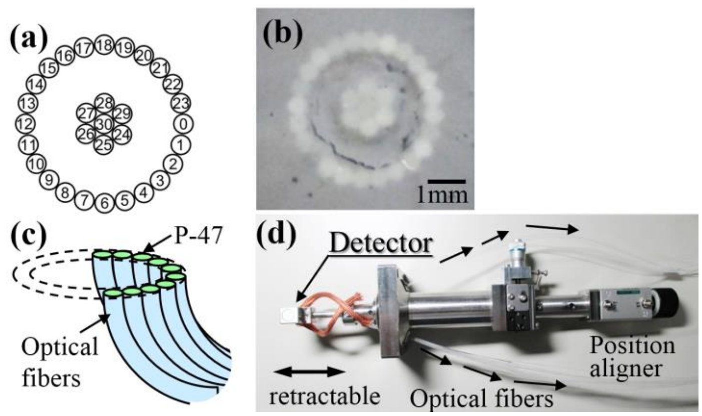

Figure 2. Developed annular pixel array detector. (a) layout of 31 channels, (b) a photograph of (a), (c) a schematic drawing of detector structure (d) a photograph of the detector mount stage.

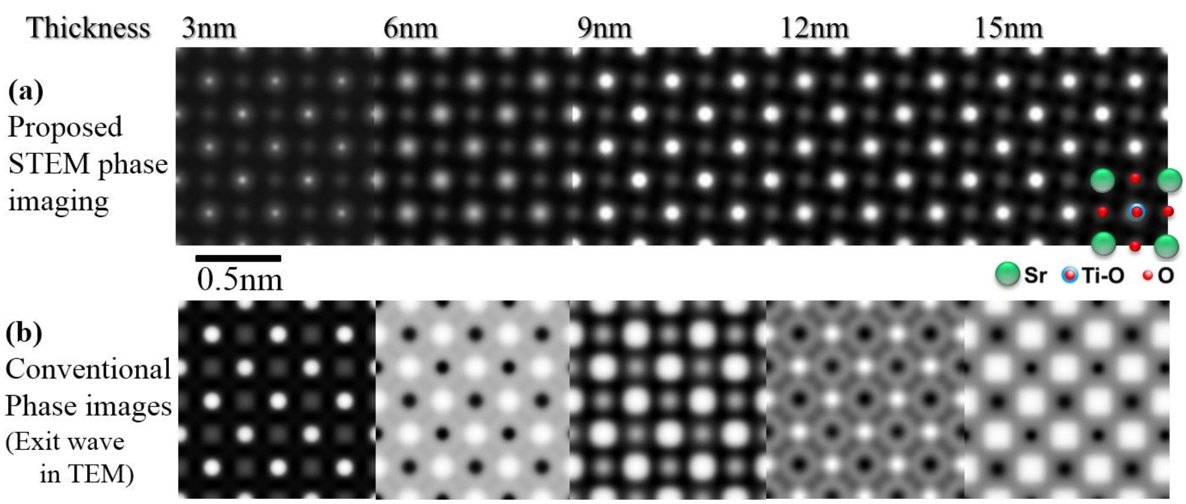

Figure 3. Simulated images of SrTiO3 [100] having different thicknesses from 3 to 15 nm.

(a) STEM phase map obtained by the proposed PRETS method.

(b) Phase in the conventional TEM corresponding to the imaginary part of the exit wave.

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