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Phase-residue Removal Based on Sparse Modeling in Electron Holography

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Electron holography is a quantitative phase-detection technique to visualize electrostatic and magnetic fields in and around nano- to micro-meter-size materials. By applying this technique to observe catalytic nanoparticles, weak electrostatic fields around a Pt nanoparticle on a TiO_2 substrate have been visualized as being locally fluctuated [1]. The precision of phase detection can be improved by increasing electron doses and enhancing visibilities of hologram fringes. The precision of ~2π/1000 rad is achieved by averaging a vast number of phase images.

The phase image in electron holography is reconstructed from corresponding electron holograms. The wrapped phase image, in which the range is restricted within $(-\pi, +\pi]$, is commonly obtained by inverse trigonometric computation. The true phase image is computed using sophisticated phase unwrapping algorithms (for example [2]). However, when the phase image includes phase residues (or phase singularity points), the discontinuity of 2π rad at the residues arises and the true phase values become ambiguous. Because the discontinuity does not disappear by averaging many phase images, residue removal is indispensable for quantitative holography analysis.

We used a sparse modelling technique [3, 4] for removing the residues in a phase image. Phase residues were first detected automatically in a wrapped phase image. A corresponding area including a residue was then cropped and repaired by patching a few predefined images on the based of sparse modeling. Finally, residue detection and repair were repeated until all residues were removed.

We tested residue removal on a real image, which was an atomic-resolution phase image at a Pt/TiO_2 boundary observed using a 1.2 MV holography electron microscope [5]. The removal process was conducted on Gatan DigitalMicrograph 3.42 software, and the scikit-learn module was used as a sparse coder. Figure 1(a) shows an original reconstructed phase image at an atomic resolution. There were discontinuities, which had 2π rad phase jump. One of them is indicated with a white rectangle and the magnified image is superimposed. Figure 1(b) shows a repaired phase image without any discontinuities. Thus, we successfully demonstrated residue removal on a real phase image.

Figure 2 shows a peak-signal-to-noise ratio (PSNR) plot for the original and repaired phase images. The reference image for the PSNR calculation was set to a low-noise phase image at the same view observed with an electron dose of ~25 counts/pixel. As the electron dose decreased, the PSNR for the original phase image severely decreased, because the phase residues in the image increased. The PSNR for the repaired phase images gradually decreased. This is because there are few residues in phase images at any dose.

In conclusion, we demonstrated the removal of the phase discontinuities caused by residues in electron holography. Residue removal is important for high precision quantitative electrostatic analysis of functional materials such as a nanoparticle catalyst [6].

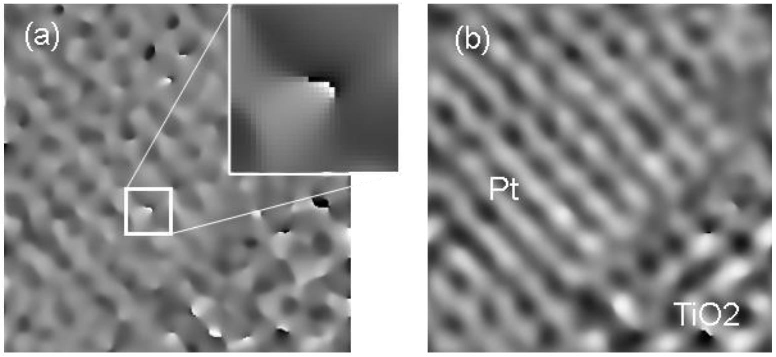

Figure 1. (a) Original phase image including discontinuity caused by phase residues. (b) Repaired phase image

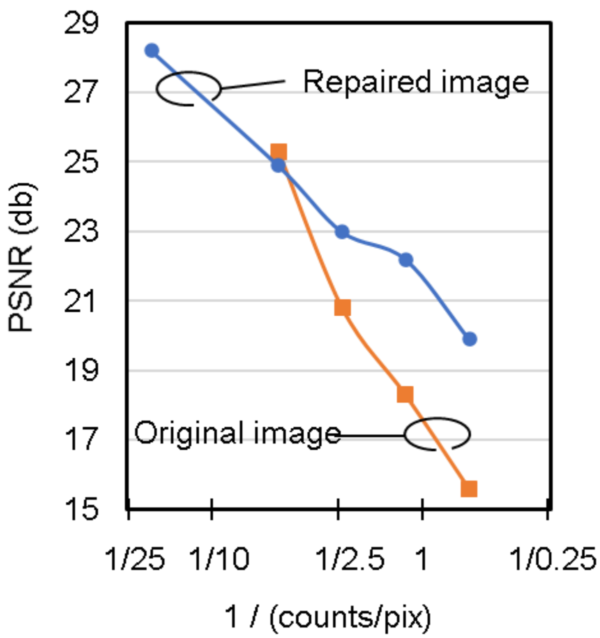

Figure 2. PSNR plot for original phase images and for repaired phase images compared with a reference image observed with high electron dose (~25 counts/pixel).

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