Off-axis electron holography phase-shifting techniques combined with summation for routine high sensitivity and high spatial resolution phase maps

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Off-axis electron holography is a powerful technique that can quantitatively map fields with nm-scale resolution. This technique is sensitive to contributions, such as electric, magnetic and strain fields. Phase maps are reconstructed from the interference patterns using Fourier processing which normally limits the spatial resolution to two times the hologram fringe spacing.

We will show developments to provide phase maps with both high sensitivity and high spatial resolution. Hologram summation is used to improve sensitivity [1]. This is combined with phase-shifting techniques that are used to improve the spatial resolution by erasing the autocorrelation term of the holograms. Two different phase-shifting techniques are presented, the first called double-exposure [2] and a second referred as phase-shifting [3]. The hologram acquisition has been modified to acquire series of holograms with a determined phase offset induced by the beam tilt. The double-exposure method uses 2 holograms with a phase offset of π, to erase the center-band with few modifications of the usual Fourier reconstruction. Thus the spatial resolution of the reconstruction procedure is doubled. Phase-shifting method uses at least 3 holograms with phase shift varying linearly between 0 and 2π. A specific reconstruction procedure is performed in direct space, using the hologram intensities, to reconstruct the phase for each pixel of the camera independently from the hologram fringe spacing. In this case, the spatial resolution of the phase map is limited by the spatial resolution and instabilities of the TEM.

Modifications in hologram acquisition and processing will be discussed within the frame of the two different methods (summation + double-exposure and summation + phase-shifting) based on different materials and theory. We show that these methods can be implemented for routine holography measurements on all microscopes with the development of a plugin for DigitalMicrograph used for TEM acquisition and reconstruction of holograms series.

Figure 1 shows an example based on the reconstruction of the geometric phase of a multilayer epitaxy SiGe/Si sample. The dark-field electron holography experiment was performed with a FEI Titan microscope, in image-corrected Lorentz mode configuration. Figure 1(b) plots the improvement in phase sensitivity with summation, up to 2π/630 rad for a series of 32 holograms. (c) proves the erasing of the center-band with the double-exposure method. (d) shows the doubling of spatial resolution down to the fringe spacing for strain maps calculated by using the double-exposure method, and the strain sensitivity improvement down to 0.02 %.

Figure 2 shows a high-resolution holography experiment performed on a Si [110] sample. Holograms were acquired with 2 s exposure time on a FEI Titan image-corrected TEM. Hologram interfringe in (a) is 0.21 nm, larger than Si <220> interatomic distances, and does not separate side-bands from center-band for a Fourier reconstruction (see (b)). However the phase reconstruction using the phase-shifting method with a series of 4x15 holograms is independent from the interfringe and shows the atomic structure with the Si atoms resolved in (c), as proved in the Fourier transform of the phase in (d). The sensitivity is 2π/250 rad.

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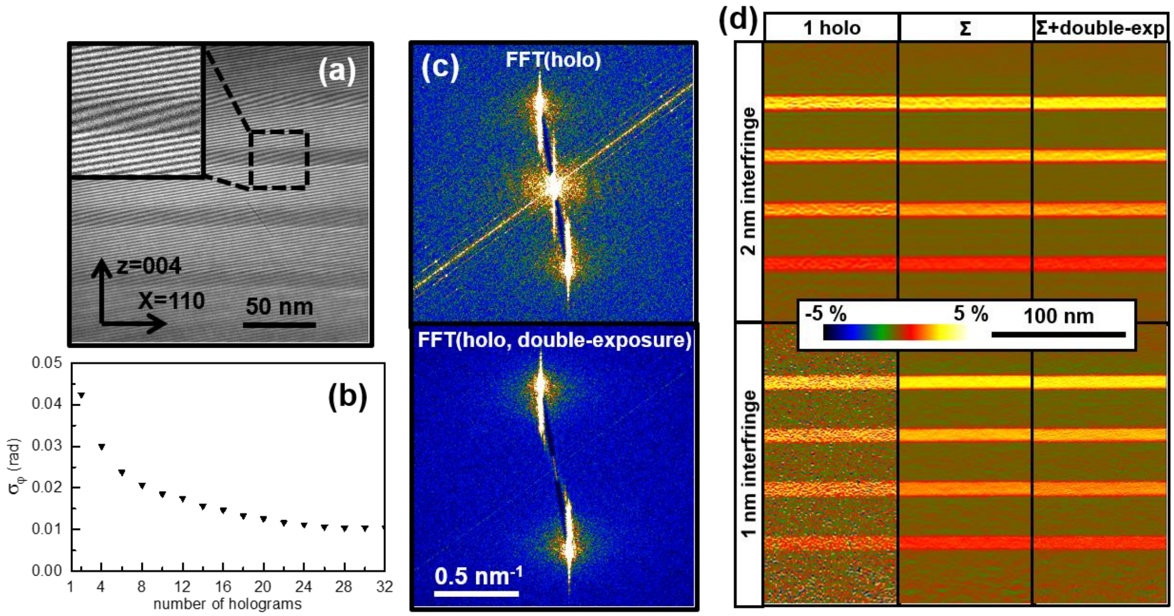

Figure 1: (a) 004 dark-field hologram, with a 2 nm fringe spacing, of a multilayer epitaxy SiGe/Si sample. (b) Standard deviation of the reconstructed phase image as function of the number of holograms which are summed. (c) Fourier transform of the hologram without (top) and with (bottom) the double-exposure method showing the erasing of the center-band. (c) Out-of-plane strain maps (ε_{zz}) calculated from geometric phase images obtained from holograms with 2 different fringe spacings (2 nm and 1 nm) and 3 different reconstruction methods (usual, summation and summation + double-exposure).

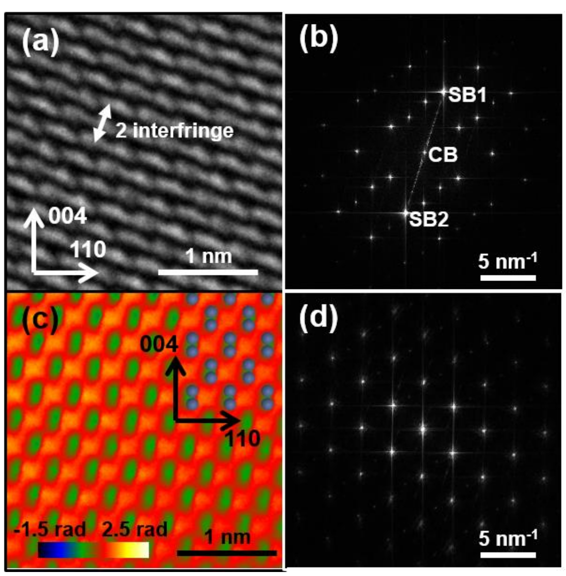

Figure 2: (a) High resolution hologram of a Si sample in [110] zone axis, with a 0.21 nm fringe spacing. (b) Fourier transform of the hologram with side-bands (SB) not separated from center-band (CB). (c) Phase image reconstructed with the phase-shifting technique combined with summation, part of the Si lattice structure is overlapped. (d) Fourier transform of the phase map showing the atomic planes resolved.