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Effect of Sampling on Geometric Phase Analysis Sensitivity for Strain Measurement in Scanning Transmission Electron Microscopy

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The Geometrical Phase Analysis (GPA) method [1] is a data processing technique massively used nowadays to measure the deformation on images composed of periodic features. Dark-Field Electron Holography [2], High-Resolution Scanning Transmission Electron Microscopy (HRSTEM) [3], and STEM Moiré GPA [4,5] are three examples of strain characterization techniques routinely using the GPA method to calculate the deformation maps with a resolution down to a few nanometers. A sensitivity of roughly 10^{-3} for HRSTEM GPA and 10^{-4} for DFEH were reported in previous studies [3,6,7]. The resolution and sensitivity in GPA are nonetheless closely linked. During the GPA process, a mask is used in Fourier space to isolate a spatial periodicity and the spatial evolution of the associated spatial frequency is displayed as a phase. Often a Gaussian function is used for the mask and its standard deviation is related to the resolution of the phase map [8]. The resolution can be seen as the area where the deformation is averaged, therefore the contribution of noise can be diminished with worse resolution. The common practice is to adjust the resolution to obtain a certain level of precision. The theoretical description suggests that the link between resolution and sensitivity is purely a processing effect. However, in practice, different levels of sensitivity are observed on strain maps recorded with different experimental conditions while keeping identical GPA processing settings. The effect of sampling, often neglected in HR-STEM imaging, becomes significant in large field of view strain maps and it is proposed in this study to highlight the hidden link between the pixel spacing and the sensitivity.

In the subsequent experiment, an InP Zinc Blende crystal structure substrate is used as our unstrained reference. Two HRSTEM electron micrographs and two STEM Moiré holograms (SMHs) were recorded with the following pixel spacing of 11 pm, 42 pm, 116 pm and 233 pm respectively. Typical acquisition times were used for both imaging conditions: 4 µs for the HRSTEM micrographs and 50 µs for the SMHs (the higher dwell time for the SMH is required to get a good contrast between the Moiré fringes). All the strain maps were processed using the same GPA method with a Gaussian mask radius of 20 pixels centred on the two non colinear (111) reflections. Results of the strain experiments are summarized in Figure 1. A Gaussian fit of the deformation distribution is highlighted in Figure 2 for each experiment to sense the statistical differences. The standard deviation from each numerical fit is dropping from $2.84*10^{-3}$ using a pixel spacing of 11 pm to $3.68*10^{-4}$ with a pixel spacing of 233 pm demonstrating a clear improvement of the sensitivity with increasing pixel spacing. The effect here is partially related to the sampling parameter changing the relative distribution of the reflections variations (strain) and of the noise in reciprocal space. By increasing the pixel spacing the same level of deformation is more separated from the unstrained frequency in Fourier space and is therefore more distant from the parasitic phase noise. As a result, lower level of deformation becomes detectable, making potentially possible to detect lower level of deformation down to 10^{-5} with very large field of views. Nonetheless, other experimental constraints still limit the gain of sensitivity with increasing pixel spacing. For the case of STEM, other sources of scanning noise are appearing with the longer dwell times used for the SMHs. Furthermore, the scanning coils cause distortions interpreted as a parasitic strain field. Finally, the off-axial spherical aberrations (not corrected in traditional aberrations corrected STEM microscope) evolve linearly with the field of view and become significant with large pixel spacing, thus affecting the phase contrast. Improvement in the hardware would be required to take full benefit from the GPA great sensitivity for large field of view applications [9].

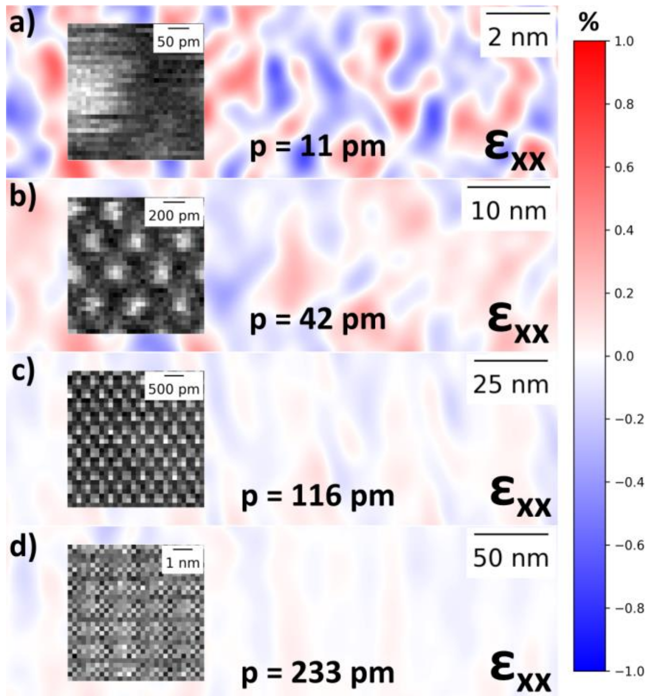

Figure 1. Strain results obtained on an unstrained InP at different sampling conditions. a)-b) Section of HRSTEM GPA strain maps along the [110] direction (horizontal direction ε_{xx}) from HR-STEM electron micrographs recorded with a pixel spacing of 11 pm and 42 pm respectively. c)-d) Section of STEM Moiré GPA strain maps along the [110] (horizontal direction ε_{xx}) direction recorded from STEM Moiré holograms recorded with a pixel spacing of 116 pm and 233 pm respectively. On all four strain maps, one 50 x 50 pixels inset of the original micrograph is shown.

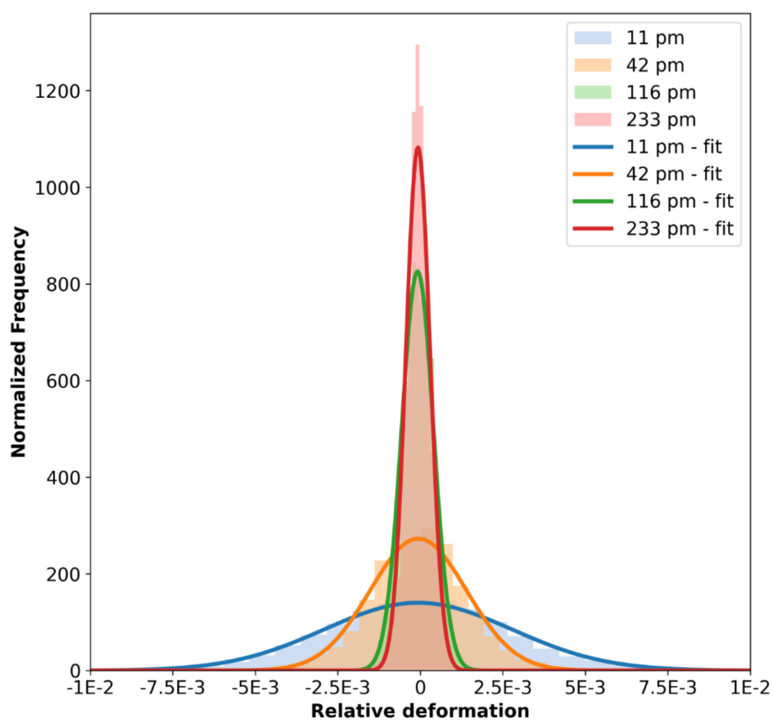

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Figure 2. Frequency distributions of the relative deformation from the strain maps in Figure 1 a)-d) and their associated gaussian fits.

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