Phase STEM imaging at the limit of resolution, contrast and dose

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We demonstrate state of the art direct phase STEM imaging at the limit of resolution, contrast and dose. We use the iDPC-STEM [1,2] and ADF-STEM techniques simultaneously [3] to resolve the atoms at sub-Å scale for various different samples and under various extreme conditions.

The First example shown in Fig. 1 is GaN, where both the Gallium and Nitrogen dumbbells in a GaN crystal in [10-11] orientation, which each have a separation of only 63 pm, are visible. We present extended versions of the results shown in [3] and elaborate on the fact that iDPC-STEM allows fine-tuning the microscope while imaging. Furthermore, we demonstrate that the ratios of the measured intensities of the different atom columns match very well with theoretical predictions based on simulations.

The second example, shown in Fig. 2, involves imaging of extremely light elements, such as lithium, the third element in the periodic system. We show that Li can be imaged directly in $LiTi_2O_4$ using iDPC-STEM and we support this with simulations and theoretical predictions.

The last example, shown in Fig. 3, stresses the huge advantage of using iDPC-STEM imaging at very low dose conditions. Zeolite (ZSM-5 [010] [4]) is an example of very beam sensitive materials that are unable to withstand more than ~ 5000 e/Å^2. We show high quality atomic resolution images of this material using iDPC- and ADF-STEM and a dose of only 1000 e/Å^2. It is important to stress that only thanks to the low dose sensitivity of iDPC-STEM is was possible to enable focusing and stigmation under such low dose conditions to obtain this high quality images. We also show that it is possible to study the gradual degradation of the sample due to beam damage with iDPC-STEM.

[1] I. Lazic, E.G.T. Bosch and S. Lazar, *Ultramicroscopy* **160** (2016) 265-280.

[2] I. Lazic, E.G.T. Bosch, *Advances in Imaging and Electron Physics* **199** (2017) 75-184.

[3] E. Yücelen, I. Lazic, E.G.T. Bosch, *Scientific Reports* **ISH** (2018) pp-pp.

[4] J. Su et al, *Microporous and Mesoporous Materials* **189** (2014) 115-125.

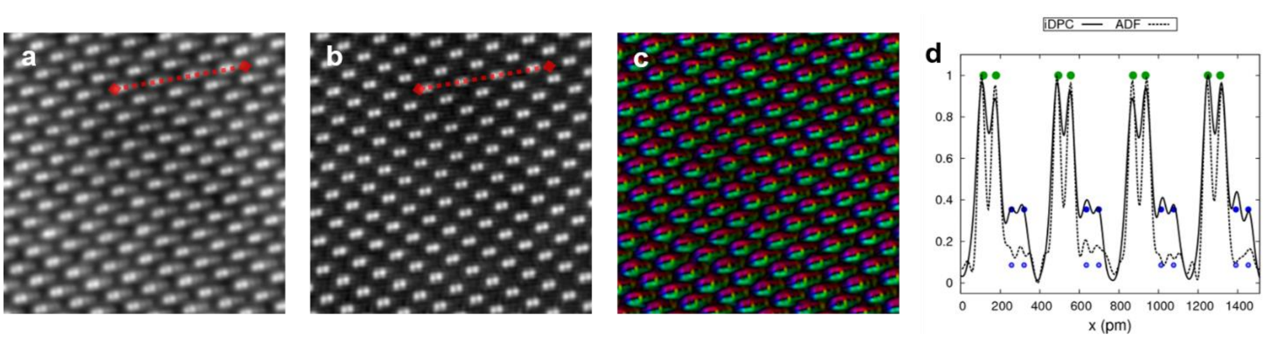

Figure 1. (a) iDPC-STEM **(b)** ADF-STEM and **(c)** DPC vector image of GaN in [10-11] orientation. The FOV is 3 nm. **(d)** Normalized intensity profile plots of iDPC- (solid line) and ADF-STEM (dashed line) along the indicated red dashed lines. Green and blue dots: position and expected intensity of the columns.

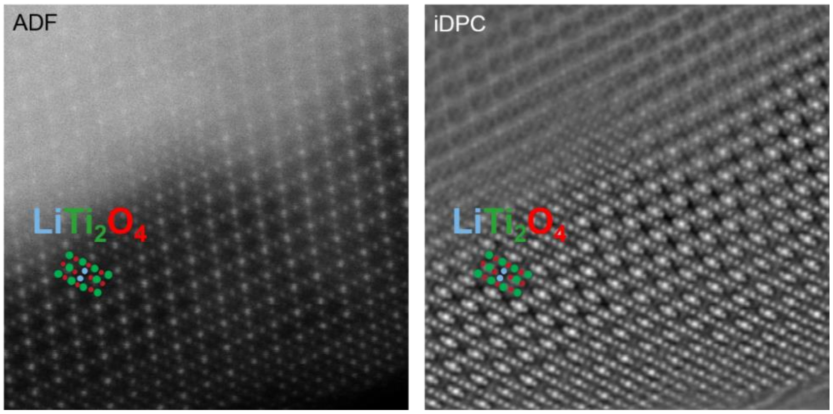

Figure 2. Li within $LiTi_2O_4$. Simultaneous ADF-STEM (left) with iDPC-STEM (right) acquired at 300 keV with convergence semi-angle of 20 mrad. Both Li and O columns are visible in iDPC-STEM image.

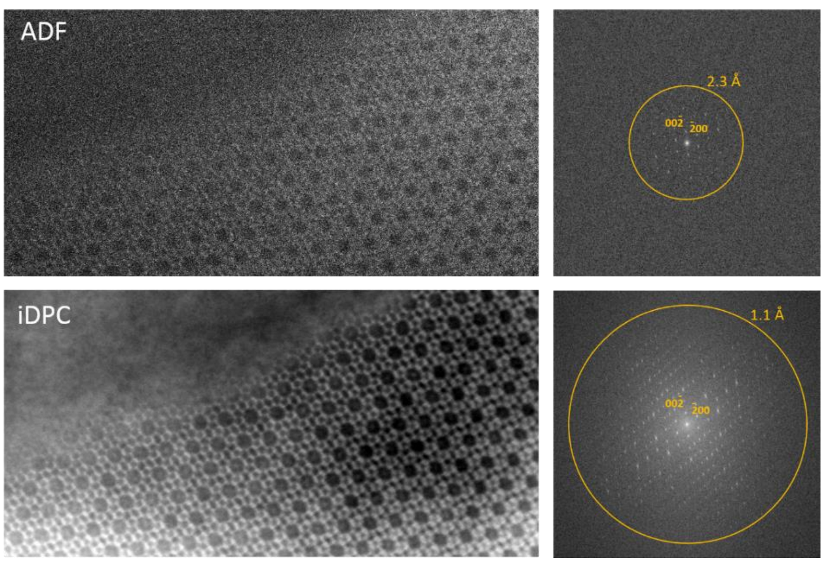

Figure 3. Comparison between ADF-STEM (top) and simultaneous iDPC-STEM (bottom) image (left) of ZSM-5 and their corresponding Fourier transforms (right). Applied dose: 1000 $e^-/Å^2$. Images acquired at 300 keV with convergence semi-angle of 20 mrad.