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Meeting-report

An Electron Computational Ghost Imaging Setup for High Resolution Imaging

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The continuous strife for enhanced lateral resolution in transmission electron has been always related to ability to reduce the unavoidable positive spherical aberration of cylindrical lenses. These has led during the years to the introduction of aberration correctors, complex systems comprising more lenses and multipoles, typically hexapoles or octupoles now able to correct aberrations up to the 6th order.

However, in this quest a less direct method (i.e., ptychography) has reached a breakthrough that allowed overcoming the current resolution limits. It is a computational imaging methods that relies retrieving the scattering from redundant information in the multiple diffraction imaging [1].

We introduce here a different computational method called Computational Ghost Imaging (CGI) [2, 3], that consists in recovering the transmission function of the sample by using structured illumination instead of the plane waves typical of traditional imaging modes or the convergent probes used in scanning modes. One of the interesting feature of CGI is that it can be partially interpreted as an optical inverse ptychography but has a different range of applications and relies on a different hardware.

In a recent paper [4] we introduced a way of performing CGI with electrons using a new electro-optical device based on the Micro Electro-Mechanical System (MEMS) technology.

Illumination patterns are produced by shaping the electron beam with a specific set of electrodes in the probe-forming aperture and are shone on the sample in quick succession. For each pattern, a suitable signal is collected by means of a single-pixel or bucket detector such as the bright field (BF) and annular dark field (ADF) detectors. Energy dispersive X-ray spectroscopy (EDX) and electron energy loss spectroscopy (EELS) spectrometers are also suitable single pixel detectors.

The full transmission function is reconstructed from this set of measurements by using specialized inversion algorithms that have been proposed during the years for the optical counterpart [5]. Knowledge of the precise patterns intensity is mandatory for a correct reconstruction.

One of the main advantages of the CGI scheme is its flexibility. Illumination patterns can be adaptively chosen and custom tailored for specific applications in order to target, for instance, high speed, selectivity or resolution. However, if in light optics, spatial light modulators offer the freedom to produce nearly any desired pattern shape, electron optics does not offer the same versatility. The design of an electron CGI experiment should then start from the design of the device itself.

In this contribution we propose on an electron CGI experimental setup able to retrieve the image of a crystalline sample at a resolution higher than the limit imposed by spherical aberration in an uncorrected microscope. As a matter of fact, the CGI imaging scheme allows accounting for the phase of the coherent aberrations directly in the production of the illumination patterns, providing the knowledge of the major aberration coefficients.

We will follow the relevant steps of the experiment starting from the design of a new MEMS device. Of The near-optimal device reported in figure 1a is composed of 8 needles forming 4 pairs radially distributed 90° apart to each other. Each pair of needles, when correctly biased, produces a spiraling phase. Thanks to the device symmetry, the interference between the 4 vortex beams give rise to high contrast intensity fringes that are meant to mimic the general shape of an atomic lattice (figure 1b).

The second mandatory step is the production of the database of illumination patterns. These must obey specific statistical rules in order to maximize the amount of information collected with every pattern while reducing redundancies due to excessive overlap between different patterns. To this aim a robust numerical algorithm that also includes aberration phase is implemented.

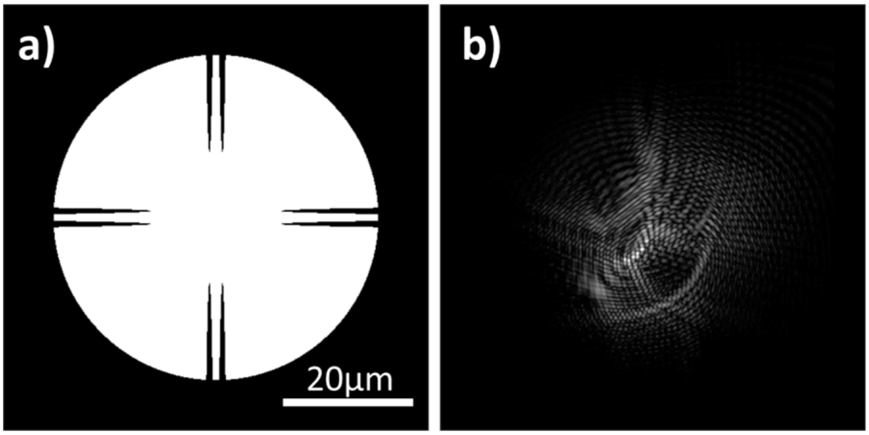

Fig. 1. a) The geometry of the pattern generator consisting in 4 pairs of electrostatic needles. b) typical shape of the illumination pattern produced by the device.

As for the signal source we consider here using the ADF detector. ADF signal is indeed directly proportional to the overlap between the sample's atomic potential and the structured beam intensity as it will be proved by means of multislice simulations. However, we could have extended the range of possible signal to different choices that are not allowed for coherent ptychography.

Figure 2 illustrates the feasibility of atomic resolution CGI by means of a direct comparison between the atomic potential of a twisted bilayer of MoS_2, used are reference image (left), its ADF-STEM image as expected when imaged using an uncorrected microscope with spherical aberration coefficient Cs=2.7mm at 300 kV (center), and the result of the proposed CGI scheme. For this amount of Cs the optimal resolution at Scherzer defocus is achieved using a 7.3mrad aperture (white dashed line). In the CGI does not have the same constraints and allows for much larger numerical apertures: here we double it to 15.4mrad obtaining a much clear representation of the sample.

The interpretation of this super-resolution in terms of the similarities and difference with ptychography are one of the most interesting directions for further discussions.

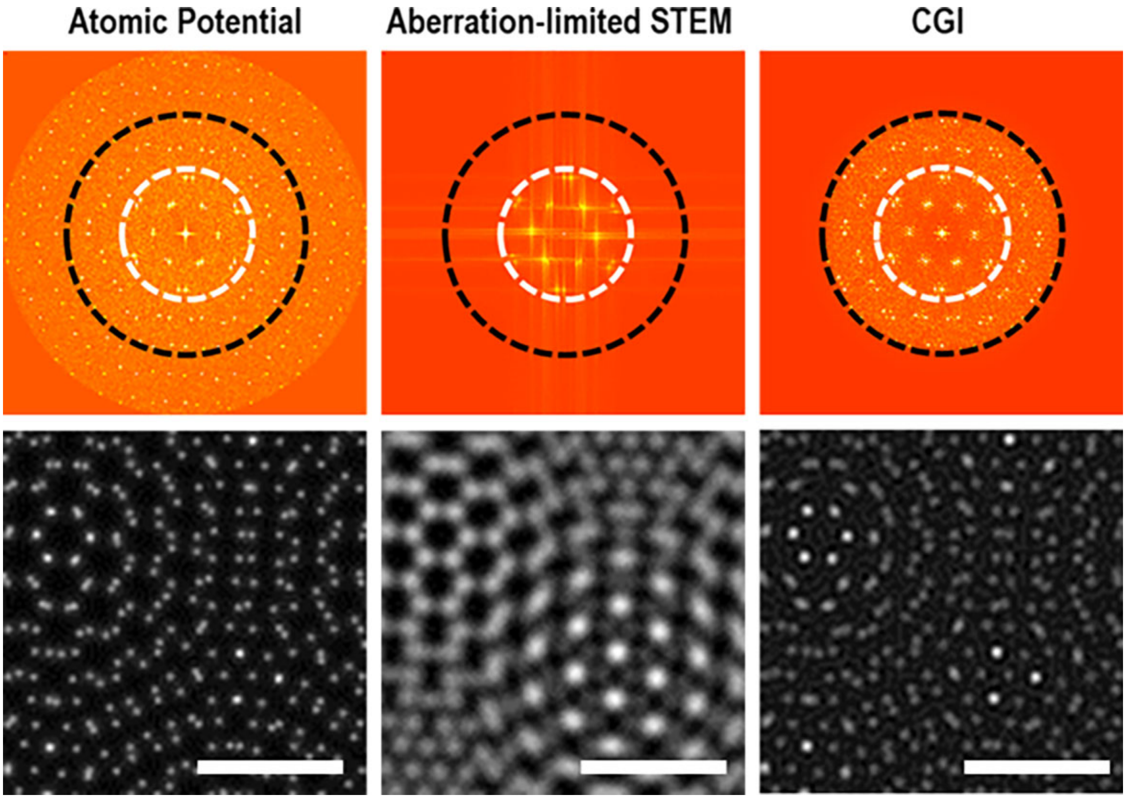

Fig. 2. a) comparison between the atomic potential of a twisted bilayer of MoS_2, the aberration-limited STEM image, and the CGI reconstructed image the sample and the corresponding FFT (scalebar is 5Å). The white dashed line correspond to the aberration limit (7.3mrad for Cs = 2.7mm at 300kV) and the black dashed circle correspond to the numerical aperture (15.4mrad).

In this work we reported on an electron analogue of computational ghost imaging that allows for the retrieval of the transmission function of a sample with the highest lateral resolution. This scheme naturally accounts for the aberration of the optical system and hence doesn't require the use of aberration correction units.

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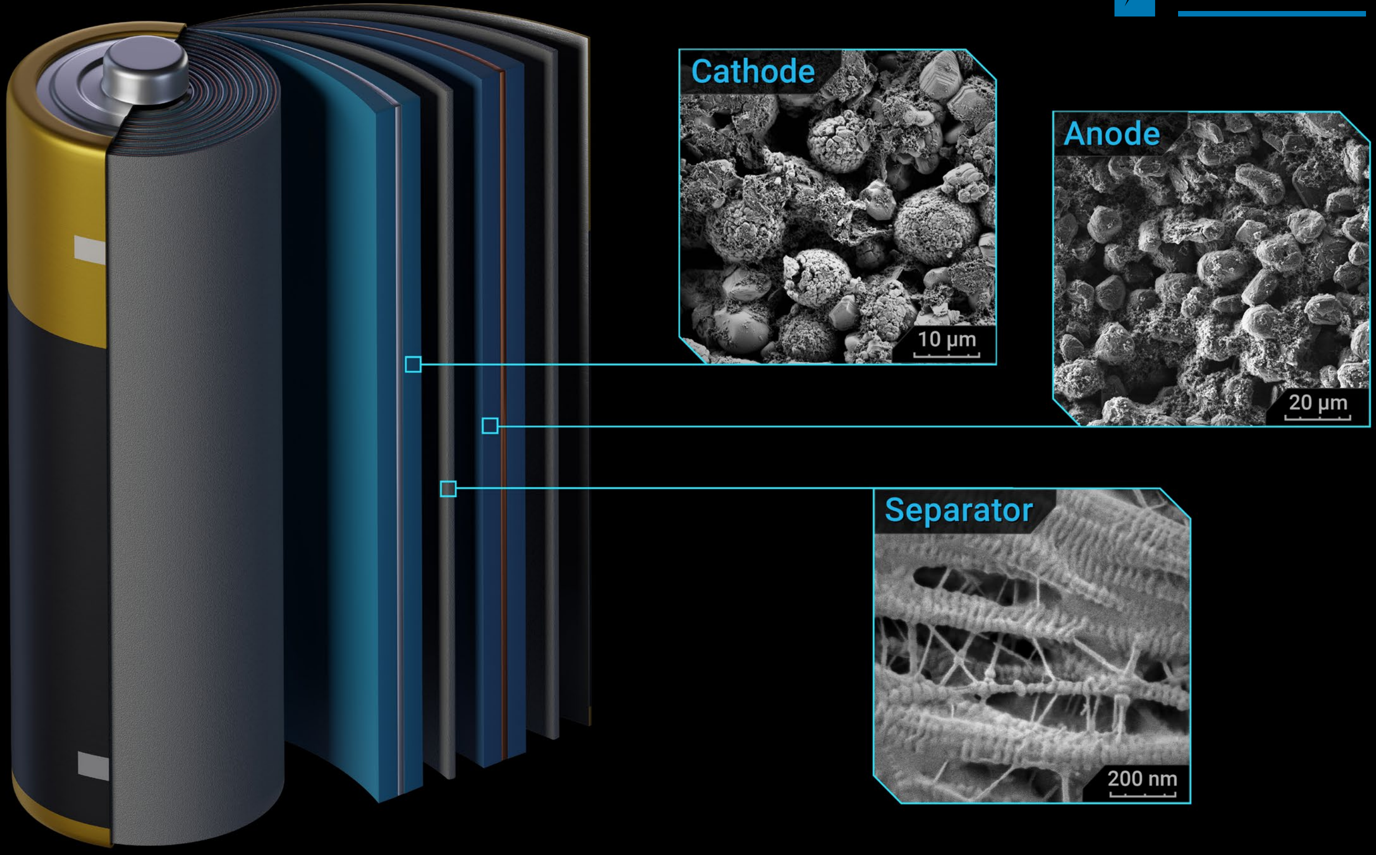

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