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MerlinEM

Application Note

Ptychography using a scanning transmission electron microscope

Key methods:

- **Ptychography**
- **4D-STEM**
- **Atomic resolution imaging**

MerlinEM is a fast, electron counting, pixelated detector for the transmission electron microscope. Its high dynamic range, radiation hardness and versatile readout system make it an exciting tool for scientific research.

MerlinEM key specifications: noiseless readout, zero dark counts; no dead time with 1-bit (18800 fps), 6-bit (3200 fps) or 12-bit (1600 fps) imaging; 30 keV - 300 keV operation; pixel size 55 x 55 µm; active area: 14 x 14 mm (256 x 256 pixels) or 28 x 28 mm (512 x 512 pixels); DQE at 60 keV: 1 at Zero frequency, 0.45 at Nyquist; MTF at 60 keV: >0.62 at Nyquist.

Electron ptychography

Electron ptychography is a computational imaging technique. It is used to generate an image of a sample from a large dataset containing interference patterns. Ptychography can recover a complex phase related to the sample, which is not directly accessible due to the nature of the physical measurements.

Ptychography in scanning transmission electron microscopy (STEM) is applied to 4D-STEM data (where a 2D diffraction pattern is acquired for each point in 2D scan) and can be used with a focused or defocused probe. A complex phase of the sample is generated post experiment by reconstruction techniques. A simplified schematic of STEM ptychography is shown in Fig. 1.

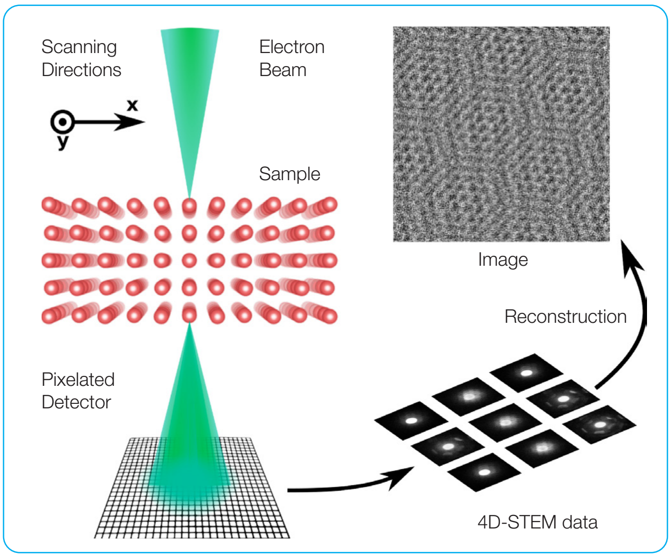

Fig 1: Schematic of 4D-STEM ptychography. 4D data is acquired by pixelated detector and resulting images are reconstructed in a computer. Reconstructed image from graphene bilayer (courtesy of Christopher S. Allen, ePSIC, Diamond Light Source, Harwell Oxford, UK)

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Ptychography in STEM

Ptychography in STEM can be separated into two distinct methods, depending on whether a focused or a defocused probe is used:

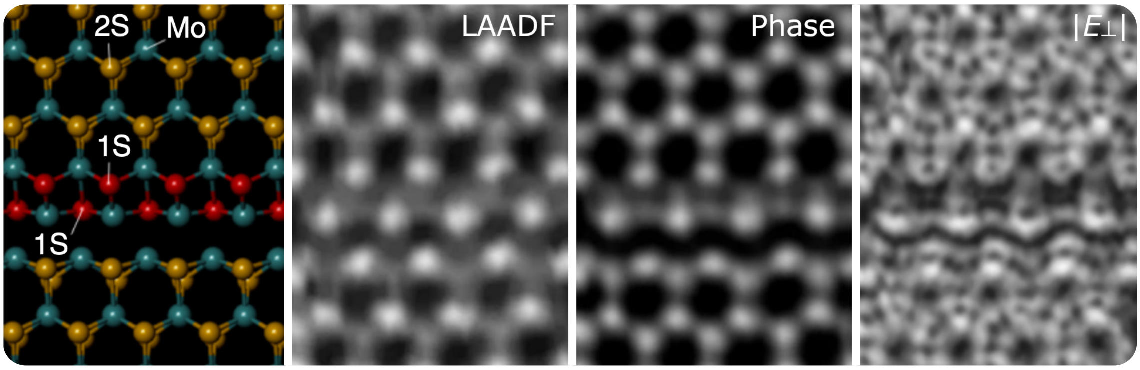

Fig 2: Focused ptychography example. From left to right: atomic model, annular dark field, phase and electric field images. The 4D-STEM data (acquired with MerlinEM detector) was used to generate phase and transverse electric field maps. Adapted with changes by BY CC 4.0 from Fang, Shiang et al. Nature communications 10. 1(2019): 1127.

- **Focused probe data** can be reconstructed with a single step method with a single-side band (SSB) algorithm based on a weak phase object approximation[1] and Wigner-distribution deconvolution (WDD)[2] which is applicable to a wider selection of samples. The main advantage of focused probe ptychography is that the additional STEM signals can be collected at the same time (i.e. HAADF, EM fields). An example images of MoS_2 sample are shown in Fig. 2.

- **Defocused probe data** can be reconstructed by iterative algorithms[3]. It can be effectively used to reduce the dose in STEM to image beam sensitive materials and cover a larger field of view of the sample. An example from a graphene sample is shown in Fig. 3.

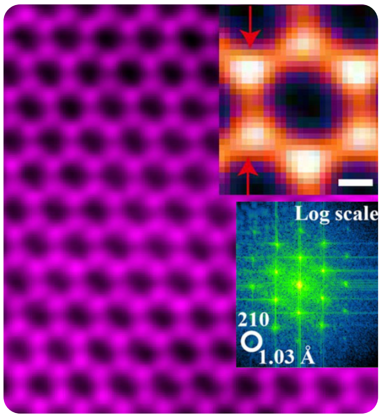

Fig 3: Image of graphene by defocused ptychography, taken with MerlinEM detector. Reproduced under CC 4.0 from Song, Jiamei et al. Scientific reports 9. 1(2019): 3919.

Electron ptychography is a very active research area. It is applicable to any probe imaging and can be used to correct lens imperfections, scanning inconsistencies and/or access higher resolution than that defined by the probe forming aperture.

MerlinEM, an electron counting detector, can be used to acquire 4D-STEM data useful for various forms of ptychography. Its single electron efficiency, zero read-out noise and high dynamic range make it a highly applicable and versatile detector technology.

1 Rodenburg, JM et al. Ultramicroscopy 48. 3(1993): 304–314.
2 Yang, H et al. Nature Communications 7. (2016): 12532.
3 Song, Jiamei et al. Scientific reports 9. 1(2019): 3919.

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Examples of ptychography publications featuring MerlinEM detector in STEM ptychography

- **O'Leary, C M et al. Microscopy and Microanalysis 25. S2(2019): 1662–1663.**

  Very fast momentum resolved STEM imaging (>10,000 fps) was used to image convergent beam electron diffraction (CBED) with only tens of electrons per probe position. An example of beam sensitive imaging was given for a ZSM-5 Zeolite sample with a dose as small as ~ 200 e / A^2.

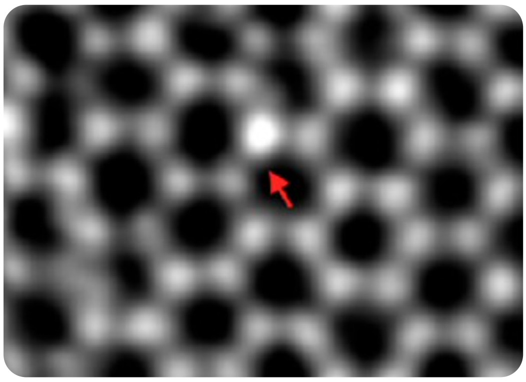
  Note: The limit of 1-bit imaging of MerlinEM is ~18,800 fps which is getting closer to standard STEM speeds with an annular detector (53 μs pixel dwell time).

- **Wen, Y et al. Nano letters 19. 9(2019): 6482–6491.**

  2D materials were studied by 4D-STEM. A combination of electron ptychography, electric field imaging and virtual annular detection was used to identify low and high atomic number atoms simultaneously in a single experiment.

- **Song, B et al. Physical review letters 121. 14(2018): 146101.**

  This publication demonstrates a possibility to combine EELS and Ptychography in the same experiment. By omitting bright field CBED disk, the image of the sample can be still reconstructed in ptychography. If a detector with a hole in the centre is used this would allow a free path of the bright field signal to spectrometer.



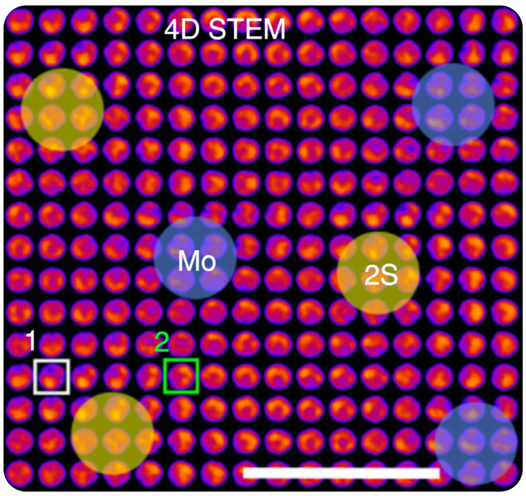
Ptychography used to resolve an additional Mo atom on MoS2 2D sample surface. Adapted with permission from Wen, Y et al. Nano letters 19. 9(2019): 6482–6491. © 2020 American Chemical Society.

- **Song, J et al. Scientific reports 9. 1(2019): 1–8.**

  Study of defocused low dose imaging for 2D materials science. MerlinEM was used as an electron counting, sensitive detector to collect a defocused STEM CBED probe.

- **Fang, S et al. Nature communications 10. 1(2019): 1–9.**

  Atomic electrostatic maps of 1D channels in 2D semiconductors using 4D scanning transmission electron microscopy. A comprehensive study of 2D materials using 4D-STEM and MerlinEM detector. A simultaneous electric field and ptychography imaging were applied to 1D interface in low dimensional materials.



Mosaic of 4D-STEM images of CBED patterns taken by MerlinEM detector in MoS2 2D material. Adapted under CC BY 4.0 from Fang, Shiang et al. Nature communications 10. 1(2019): 1–9.