Robust Imaging of Three-dimensional Polar Textures Using 4D-STEM Diffraction Imaging and Multislice Electron Ptychography

Yu-Tsun Shao, Zhen Chen, Chenyu Zhang, Harikrishnan K.P., David A Muller

Microscopy and Microanalysis, **29** (Suppl 1), 2023, 276
https://doi.org/10.1093/micmic/ozad067.126

Microscopy AND Microanalysis

Meeting-report

Robust Imaging of Three-dimensional Polar Textures Using 4D-STEM Diffraction Imaging and Multislice Electron Ptychography

Yu-Tsun Shao[1,2], Zhen Chen[3], Chenyu Zhang[2], Harikrishnan K.P.[2], and David A. Muller[2,4]

[1]*Mork Family Department of Chemical Engineering and Materials Science, University of Southern California, Los Angeles, CA, USA*
[2]*School of Applied and Engineering Physics, Cornell University, Ithaca, NY, USA*
[3]*School of Materials Science and Engineering, Tsinghua University, Beijing, China*
[4]*Kavli Institute at Cornell for Nanoscale Science, Ithaca, NY, USA*

Topological structures consisting of electric dipoles have recently gained considerable interest due to the potential applications as information carriers in next generation nanodevices. These particle-like objects have been recently realized in epitaxially-strained oxide heterostructures, and various dipolar textures have emerged as polar vortices [1], polar skyrmions [2] or merons [3], and dipolar waves [4]. As the polar textures are intrinsically nm-sized, three-dimensional objects, this poses a challenge for visualizing and characterizing their 3D detailed structure at the atomic scale. Conventional scanning transmission electron microscopy (STEM) imaging modes such as high-angle annular dark-field (HAADF) or differential phase contrast (DPC) enables the direct measurement of the projected atomic column displacements from polar distortions. However, given the 3D nature of the topological polar textures and the strong electrostrictive coupling between polarization and strain, crystal mis-tilt is ubiquitous and intrinsically inevitable across domain boundaries and in complex topological structure. For example, a slight crystal mis-tilt of as small as 0.1° may complicate and dominate the interpretation of DPC-/HAADF-STEM images [5, 6].

To meet this challenge, we developed two 4D-STEM variations to robustly image the polarization in complex topological textures. First, we show that the polarization information can be decoupled from crystal mis-tilt artifacts by recording polarity-sensitive Kikuchi bands and chirality-sensitive Bijvoet pairs at every probe position using an electron microscopy pixel array detector (EMPAD) [7, 8]. Examples include the mapping of chirality, strain, and polarization in individual polar skyrmion and meron. Second, we demonstrated robust depth sectioning by retrieving the 3D electrostatic potential of the sample using multislice electron ptychography, which provides deep sub-Å lateral resolution simultaneously with 2.9 nm depth resolution. This high precision measurements of 3D structural distortions enables solving the unknown polar textures in complex oxide heterostructures.

4D-STEM has advanced the study of materials at a variety of length scales, from the highest-resolution imaging to millimeter-scale mapping of structures and properties. Recent development of novel 4D-STEM techniques further expands our capability to study beam-sensitive samples, and improvement in saturation current and detector speeds allows for in-situ experiments. This symposium covers the applications of 4D-STEM in the study of biological and functional materials, and developments of new data analysis methods and best practices to further advance quantitative and multiscale characterization [10].

References

1. AK Yadav *et al.*, *Nature* **530** (2016), p. 198.
2. S Das *et al.*, *Nature* **568** (2019), p. 368.
3. Y-T Shao *et al.*, arXiv:2101.04545 (2020).
4. L Caretta *et al.*, *Nature Materials* **22** (2022), p. 207.
5. I MacLaren *et al.*, *Ultramicroscopy* **154** (2015), p. 57.
6. Y-T Shao *et al.*, *Microscopy and Microanalysis* **25**(S2) (2019), p. 1938.
7. MW Tate *et al.*, *Microscopy and Microanalysis* **22** (2016), p. 237.
8. HT Philipp *et al.*, *Microscopy and Microanalysis* **28** (2022), p. 425.
9. Z Chen *et al.*, *Microscopy and Microanalysis* **27**(S1) (2021), p. 2146.
10. Work supported by the AFOSR Hybrid Materials MURI, award # FA9550-18-1-0480 and the Army Research Office under the ETHOS MURI via cooperative agreement W911NF-21-2-0162. Facilities supported by the National Science Foundation (DMR-1429155, DMR-2039380, DMR-1719875)