



# Book of Abstracts

**USER MEETING & *In situ* ACADEMY**

March 25th, 2026



**Utrecht  
University**

## SCHEDULE

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9:00 – 9:15	Sign in with Coffee and Tea	
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10:00 – 10:15	Kang, Y., <i>MPI for Sustainable Materials, Düsseldorf</i> From Operando Insights to Atomic-Scale Design of Sustainable Catalytic Materials	8
10:15 – 10:30	Dr. Bejtka, K., <i>Politecnico di Torino</i> Advancing Electrochemical Control in Liquid-Cell TEM	9
10:30 – 11:00	Break with Coffee and Tea	
11:00 – 11:30	<b>Keynote Lecture</b> Dr. Ortiz, N., <i>University Paris Cité, CNRS</i> <i>In situ</i> liquid phase transmission electron microscopy: from biomaterials to electrocatalysts	4
11:30 – 12:00	Prof. Demortière, A. <i>CNRS, LRCS lab &amp; RS2E1</i> T.b.t.	
12:00 – 13:00	Lunch provided by Protochips	
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14:30 – 14:45	Van Eck, D., <i>Utrecht University</i> Following the growth of carbon nanofibers from methane pyrolysis on the nanoscale	10
14:45 – 15:00	Huang, C., <i>Linköping Univeristy</i> Chemical Reshaping of MXenes via Atmospheric-Pressure Gas Treatments	11
15:00 – 15:15	Wang, X., <i>Technical University Berlin</i> From Operando Observation to Design Principles: Visualizing Dynamic Electrochemical Interfaces for Energy Technologies	12
15:15 – 15:30	Break	
15:30 – 16:00	<b>Keynote Lecture</b> Dr. Srot V., <i>MPI for Solid State Research</i> From FIB to Function: Artifact-Minimized MEMS-Compatible FIB Strategies for <i>In situ</i> (S)TEM	6
16:00 – 16:30	<b>Keynote Lecture</b> Dr. Wang, D., <i>Karlsruhe Institute of Technology (KIT), Institute of Nanotechnology</i> Watching a model catalyst at work:Pt200/CeO <sub>2</sub> under CO oxidation	7
16:30 – 17:30	Round table discussion with drinks	

## KEYNOTE SPEAKERS

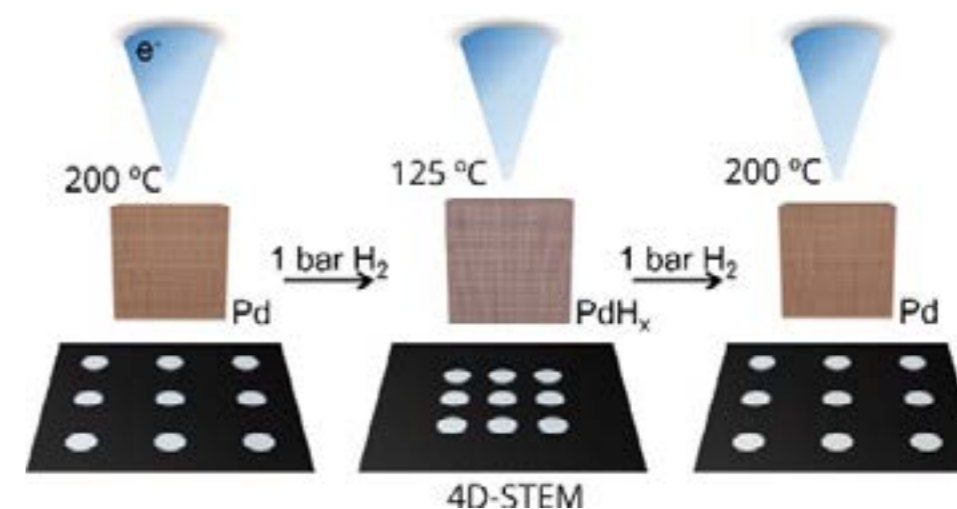


Dr. Jessi van der Hoeven  
Utrecht University

### *In Situ* 4D STEM – A New Tool for Watching Nanocatalysts under Operating Conditions

Metal nanoparticles are key materials for applications in energy storage and catalysis. How well these nanoparticles work largely depends on their structure. Lattice strain has emerged as an important structural parameter to control the functional properties of nanomaterials. For instance, in hydrogen storage applications, lattice strain can be used to control the kinetics and thermodynamics of hydrogen absorption in metal hydride nanoparticles. Furthermore, in catalysis, lattice strain can be used to modulate the binding energies of reactants at the nanoparticle surface, allowing precise control over the catalytic performance of nanoparticle catalysts. To establish accurate strain-performance relations, understanding how lattice strain in nanomaterials changes under operating conditions in the presence of reactive gasses is essential, but complicated due to the limited availability of quantitative tools to assess lattice strain *in situ* and on a single nanoparticle level.

In this talk, I will show that we can quantitatively assess strain in functional nanomaterials using *in situ* 4D-STEM. In particular I will highlight a dynamic, *in situ* study on the reversible hydride formation in palladium nanocubes by applying 4D-STEM in the presence of 1 bar H<sub>2</sub> gas to quantitatively assess the lattice strain in the Pd nanoparticles with sub-nanometer resolution [1]. 4D-STEM is a novel, advanced electron microscopy technique using a (sub)-nanometer electron probe to collect a diffraction pattern at each pixel, enabling local strain analyses within single nanoparticles. So far, 4D-STEM has mainly been applied in vacuum. In this presentation I will demonstrate that 4D-STEM can successfully be conducted in the presence of a gas as well. Using an energy filter, we maintained the high quality of the nanobeam electron diffraction patterns in the presence of 1 bar H<sub>2</sub>, and mapped the strain in individual Pd nanocubes prior to hydrogen absorption, during hydrogen uptake, and upon hydrogen release. We find that hydride formation at 125 °C leads to a homogeneous lattice expansion of ~3.1 %, and that the lattice relaxes back upon hydrogen desorption at 200 °C.



References:  
[1] Perxés Perich, M., *et al.*, *Nano Letters*, (2025), 25, 5444–5451

Dr. Nathaly Ortiz  
Université Paris Cité



### ***In Situ* Liquid Phase Transmission Electron Microscopy: From Biomaterials to Electrocatalysts**

Nathaly Ortiz Peña,<sup>1</sup> Louis Godeffroy,<sup>2</sup> Jean-Marc Noël,<sup>2</sup> Florence Gazeau,<sup>3</sup> Dris Ihiwakrim,<sup>4</sup> Ovidiu Ersen,<sup>4</sup> Damien Alloyeau<sup>1</sup>

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Direct probing of dynamical processes at the nanoscale is key to move forward in the comprehension of formation, degradation and catalytic mechanisms of biological and synthetic materials. Furthermore, a deepened understanding of such processes in realistic synthesis or functioning conditions is crucial to improve their production and implementation methods in functional devices. Thereby, the development of *in situ* and operando characterization techniques arises as a logical step in the advancement of material sciences. *In situ* liquid phase transmission electron microscopy (LP-TEM) is part of the thriving characterization techniques allowing real time monitoring with nanometric resolution of processes taking place in liquid environments and contributing to the overall comprehension of solid-liquid or liquid-liquid interfaces. Herein, we will show some examples of how *in situ* LP TEM have brought light to new aspects of the behavior of materials in their formation and working environment.

In a first instance, we will discuss the nucleation and growth of iron oxide nanoparticles in organic media displaying non-classical nucleation pathways. Then, we show a collaborative study to assess whether MoS<sub>2</sub> nanosheets pose a potential hazard to the lung environment and how it can be related to the fate and biotransformations of these nanomaterials over 1 month. To do so, we traced the mechanisms of nanotransformation of MoS<sub>2</sub> patches in intracellular biomimetic media using *in situ* LP-TEM. Then, we will discuss some preliminary results of our current research regarding the study of electrocatalysts for electrolyzers and fuel cells. In this study we have implemented a complementary methodology to track the precipitation of Ni(OH)<sub>2</sub> on top of Pt nano-assemblies using electrochemical LP-TEM, which allowed to verify the growth of a layer around the Pt nano-assemblies during cyclic voltammetry and have correlated to other microscopy techniques such as interferometric optical microscopy and scanning transmission x-ray microscopy allowing to paint a multi-scale picture of the reactivity.

Dr. Matthew Lindley  
The University of Manchester



### **Exploring the Capabilities of *In Situ* TEM: From Commercial Cells to Custom Platforms**

Matthew Lindley<sup>1\*</sup>, Rui Zhang<sup>1,2</sup>, Sam Sullivan-Allsop<sup>1,2</sup>, Nick Clark<sup>1,2</sup>, James Paterson<sup>3</sup>, Dogan Ozkaya<sup>4</sup>, Manfred Schuster<sup>4</sup>, Thomas J.A. Slater<sup>5</sup>, Roman Gorbachev<sup>2,6</sup>, Sarah J. Haigh<sup>1,2</sup>

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Commercial *in situ* transmission electron microscopy (TEM) holders have made it possible to routinely study materials in controlled gas and liquid environments, opening new opportunities to link nanoscale structure and chemistry with operating conditions that are relevant to industrial processes.[1] However, for many researchers entering the field, an important challenge lies in understanding both what kinds of studies these systems currently enable and how their capabilities continue to evolve. To explore this, we draw on a series of recent studies to illustrate how *in situ* platforms can be used to address practical questions in catalysis and materials science, while also highlighting ongoing efforts to extend their application and performance.

Using commercial gas cells/holders, we investigate the activation and evolution of Co/TiO<sub>2</sub>-based Fischer-Tropsch catalysts, revealing how Mn promoter additions and thermal treatments influence nanoparticle size, dispersion, and chemical state.[2] These experiments demonstrate how environmental control, combined with complementary analytical techniques, can provide insight that is difficult to access using conventional ex situ methods. We discuss the modifications made to commercial gas cells using multilayer graphene windows as an example of how existing platforms can be adapted to push their analytical limits. By reducing electron scattering while retaining compatibility with established holder designs, this approach enables improved imaging contrast and enhanced sensitivity for electron energy loss spectroscopy (EELS), allowing elemental and oxidation-state mapping at increased resolution (Figure 1). We also introduce our work on custom graphene-based liquid cells[3–5], recently applied to enable atomic-resolution studies at solid-liquid interfaces. These devices support controlled encapsulation of a wide range of solvents and facilitate large-scale analysis of adatom dynamics and early-stage clustering during catalyst synthesis.

Throughout these examples, practical considerations such as signal-to-noise, spatial resolution, environmental stability, and experimental trade-offs are discussed, alongside strategies being developed to address current limitations. Together, this work highlights how commercial platforms, combined with targeted innovation, continue to expand what can be achieved with *in situ* TEM.

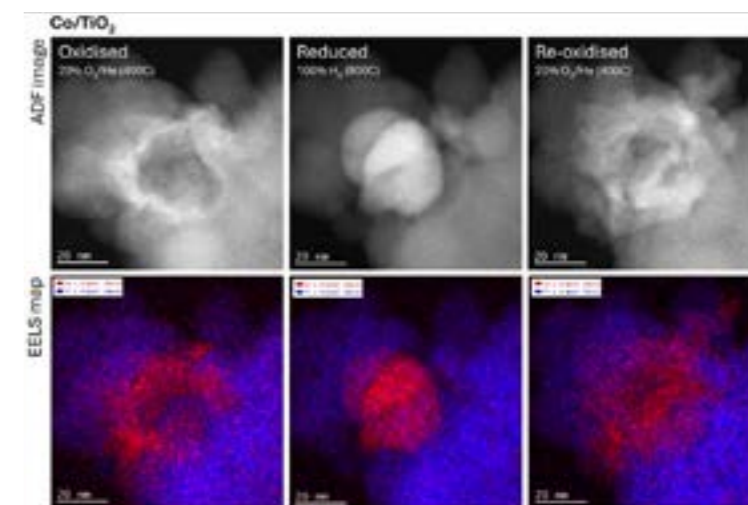


Figure 1: *In situ* STEM imaging and EELS elemental mapping of a Co/TiO<sub>2</sub> catalyst during redox cycling, showing reversible nanoparticle restructuring when exposed to dynamic reducing and oxidising environments.

#### References:

- [1] Prestat, E. *et al. ChemPhysChem* (2017) 18, 2151–2156
- [2] Lindley, M. *et al. ACS Catal.* (2024) 14, 10648–10657
- [3] Kelly, D. J. *et al. Nano Lett.* (2018) 18, 1168–1174
- [4] Kelly, D. J. *et al. Adv. Mater.* (2021) 33, 2100668 (2021).
- [5] Clark, N. *et al. Nature* (2022) 609, 942–947



Dr. Vesna Srot  
Max Planck Institute for Solid State Research

### From FIB to Function: Artifact-Minimized MEMS-Compatible FIB Strategies for *In Situ* (S)TEM

Vesna Srot<sup>1,\*</sup>, Kenan Elibol<sup>1</sup> and Peter A. van Aken<sup>1</sup>

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The fabrication of electron-transparent specimens with minimal structural damage and chemical contamination is a fundamental prerequisite for high-fidelity transmission electron microscopy (TEM) and scanning transmission electron microscopy (STEM) investigations. Focused ion beam (FIB) techniques are widely employed for site-specific lamella preparation. However, conventional FIB workflows frequently introduce preparation-induced artifacts, including amorphization, ion implantation, and contamination by gallium (Ga) and platinum (Pt), which can significantly alter the intrinsic physical and functional properties of the investigated materials. These limitations are particularly critical for *in situ* experiments on micro-electro-mechanical systems (MEMS) platforms, where sample integrity, mechanical stability, and electrical reliability are essential for quantitative biasing and electro-thermal measurements.

Here, we present a systematic development of advanced *in situ* sample preparation strategies for MEMS-based (S)TEM, integrating novel FIB lift-out geometries with artifact-minimized transfer and thinning protocols. A recently developed alternative lift-out configuration enables direct lamella attachment to MEMS chips, eliminating intermediate grid mounting steps and substantially reducing the number of attachment/detachment operations and Pt fixation processes [1,2]. This streamlined workflow minimizes ion-beam-induced damage, contamination, and mechanical stress, thereby enhancing experimental reproducibility and measurement reliability. The influence of preparation parameters and lamella geometries on electrical performance was quantitatively assessed through controlled structural and electrical characterization. This methodology enables the fabrication of high-quality, mechanically robust, and electrically stable lamellae on FIB-optimized chips as well as on conventional MEMS platforms, and is broadly applicable to materials compatible with standard FIB processing.

The approach was further extended to two-dimensional (2D) layered materials, enabling the preparation of lamellae in non-conventional crystallographic orientations that are inaccessible by mechanical exfoliation [3,4]. Using indium selenide (InSe) as a model system, lamellae were extracted along multiple crystallographic directions and integrated onto electrical biasing FIB-optimized chips with engineered contact geometries [1,2]. Atomic-resolution STEM imaging and analytical spectroscopy reveal clean, defect-minimized surfaces with strongly suppressed preparation-induced artifacts, enabling reliable structure-property correlations under electrical bias.

Finally, gold emitter arrays composed of triangular nanoprisms coupled to hemispherical gold grains were directly patterned on SiNx membranes mounted on *in situ* TEM biasing chips using electron-beam lithography and thermal evaporation. Subsequent electron-beam processing enabled the formation of sub-10 nm gaps, while focused ion beam was used to refine electrical contacts, allowing precise nanoscale device integration [5].

Collectively, this work establishes a unified, artifact-minimized FIB-based methodology for MEMS-compatible *in situ* (S)TEM sample preparation. By extending recent FIB-enabled *in situ* fabrication concepts [1–5], conventional FIB workflows are transformed into a controlled fabrication strategy for MEMS platforms, providing a robust technological framework for reliable electrical, thermal, and functional characterization of nanoscale materials and devices under operando conditions.

#### References:

- [1] Srot, V., et al. *Microsc. Microanal.* (2023) 29, 596-605
- [2] Srot, V., et al. *Microsc. Microanal.* (2024) 30, 1588-1589
- [3] Srot, V., et al. *Microsc. Microanal.* (2026), submitted
- [4] Elibol, K., et al. *Microsc. Microanal.* (2026), submitted
- [5] Elibol, K., et al. *Sci. Adv.* (2026) 12, 1-13



Dr. Di Wang  
Karlsruhe Institute of Technology (KIT), Institute of Nanotechnology

### Operando (S)TEM Insights on Mass Selected Pt<sub>200</sub>/CeO<sub>2</sub> as Model Catalyst for CO Oxidation

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Mass-selected metal clusters supported on oxide surfaces serve as powerful model catalysts for probing fundamental aspects of heterogeneous catalysis. In our work, we investigate Pt<sub>200</sub> clusters supported on pulsed laser-deposited CeO<sub>2</sub>, prepared via Cluster Ion Beam Deposition (CIBD)[1] directly onto a Protochips MEMS reactor device. This setup facilitates operando Scanning Transmission Electron Microscopy (STEM), allowing real-time imaging under controlled heating and gas flow. During CO oxidation (with CO and O<sub>2</sub> as input gases), the CO<sub>2</sub> generation and the level of conversion at different temperatures have been monitored using a high sensitivity residual gas analyzer (RGA). In addition, identical location STEM experiments are also conducted to understand the effect of e- beam on the cluster dynamics and to assess its effect on the catalytic process.

Beyond operando catalytic conditions, the catalyst is examined in pure oxidative (100% O<sub>2</sub>) and reductive (100% H<sub>2</sub>) environments to visualize Pt-CeO<sub>2</sub> interactions in fresh, spent and rejuvenated states. Under oxidative treatment (≥400 °C), Pt<sub>200</sub> clusters disperse into single atomic sites, forming PtO<sub>x</sub> and Pt<sup>n+</sup>-O-Ce species[2]. Upon reduction with H<sub>2</sub> at 800 °C, cluster reformation is observed, revealing reversible structural dynamics and Strong Metal-Support Interactions (SMSI). The Ce oxidation states at both oxidized and reduced states have been analyzed using electron energy loss spectroscopy (EELS). The catalyst is tested for multiple CO oxidation cycles to assess onset, stability, and cyclability. CO<sub>2</sub> formation is confirmed via mass spectrometry with minimal sintering or redispersion of clusters observed up to 600 °C. The operando evaluation is carried out in native, oxidized, reduced, and spent states to understand the effect of the Pt-CeO<sub>2</sub> interface on the activity. The observations are compared to an analogous model catalyst tested independently in a flow reactor to validate the operando STEM findings. Difference in the operando TEM setup will be discussed. This integrated approach bridges atomic-scale imaging with catalytic performance, offering comprehensive insights into structure-activity relationships in cluster-based model catalysts.

#### References:

- [1] Fischer, A., et al. *Rev Sci Instrum.* (2015), 86, 023304
- [2] Maurer, F., et al., *Nat. Catal.* (2020), 3, 824–833

## PRESENTATIONS

### From Operando Insights to Atomic-Scale Design of Sustainable Catalytic Materials

*Kang, Y.<sup>1</sup>; Chen, X.<sup>1</sup>; Dehm, G.<sup>1</sup>; Gault, B.<sup>1</sup>; Zhou, X.<sup>1</sup>; Raabe, D.<sup>1</sup>*

<sup>1</sup>Max Planck Institute for Sustainable Materials, Düsseldorf

The transition toward a circular materials economy requires not only efficient recycling technologies but also fundamentally new design concepts for catalytic materials that enable reuse, repair, and closed-loop recovery. Here we bridge electrochemistry and advanced microscopy to establish such principles at the atomic scale.

By combining operando and liquid-phase transmission electron microscopy (TEM) with atom probe tomography (APT), we investigate the dynamic structure–property relationships of noble-metal catalysts, particularly platinum, during electrochemical deposition, dissolution, and regeneration. This correlative approach reveals nanoscale self-terminating and degradation mechanisms in real-time and provides atomistic insight into the selective recovery of Pt from spent electrodes.

Building on these findings, we aim to develop recyclable catalytic systems in which electrodeposition serves as both a synthesis and regeneration route. Electrochemically reconfigurable materials designed along these principles offer extended catalyst lifetime, reduced critical-metal consumption, and a transferable framework for sustainable design across functional material classes, including electrodes, sensors, and smart coatings.

## PRESENTATIONS

### Advancing Electrochemical Control in Liquid-Cell TEM

*Bejtka, K.*

Reaching meaningful operando conditions in electrochemical liquid-phase TEM (EC-LPTM) requires simultaneous control of mass transport and electrochemical stability within highly confined liquid-cell geometries.

In this contribution, I will discuss advances in liquid-cell designs that enable diffusion-dominated mass transport, significantly extending the accessible electrochemical operating window compared to conventional cells [1]. The impact of these optimized conditions is demonstrated through operando EC-LPTM studies of a copper-based catalyst, revealing dynamic structural and chemical evolution under electrochemical bias [2-4].

In the second part, I address electrochemical stability in confined geometries by introducing nanostructured reference and counter electrodes integrated on-chip. This approach reduces electrode polarization and potential drift, improving the reliability and reproducibility of electrochemical control during operando measurements [5]. Together, these developments provide a practical pathway toward more controlled and quantitative EC-LPTM experiments in liquid electrolytes.

References:

- [1] Bejtka K., *et al.*, *Small Methods* (2025), 9, 2401718
- [2] Gho C., Bejtka K., *et al.*, Manuscript under review.
- [3] Wahab A., Bejtka K., *et al.* Manuscript in preparation.
- [4] Wahab A., Bejtka K., *et al.*, Manuscript in preparation.
- [5] Gho C., Bejtka K., *et al.* Manuscript in preparation.

## PRESENTATIONS

### Following the Growth of Carbon Nanofibers from Methane Pyrolysis on the Nanoscale

*Van Eck, D.*

Methane pyrolysis is a promising route for low-emission H<sub>2</sub> production. This process is accompanied with solid carbon formation, which is seen as undesirable and the main bottleneck for practical implementation on an industrial scale. When using a Ni nanoparticulate catalyst under mild operating temperatures, the carbon coproduct precipitates from Ni nanoparticles as carbon nanofibers, which have interesting properties for various applications.

Gas-phase *in situ* TEM, enabled by the Protochips Atmosphere system, can be used to study these carbon nanofibers from methane pyrolysis on the nanoscale [1]. In our work, we follow a substantial number of carbon nanofibers from Ni-based catalysts to gain relevant qualitative and quantitative information on their formation, growth, and deactivation. The information obtained from these *in situ* TEM experiments is a valuable addition to ex-situ catalytic information to enable the design of superior methane pyrolysis catalysts.

References:

[1] Welling, T. A. J., et al. *J. of Phys. Chem. C* (2023), 127, 15766–15774

## PRESENTATIONS

### Chemical Reshaping of MXenes via Atmospheric-Pressure Gas Treatments

*Huang, C.<sup>1\*</sup>, Qin, L.<sup>2</sup>, Rosen, J.<sup>2</sup>, Persson, P.O.Å.<sup>1</sup> and Palisaitis, J.<sup>1</sup>*

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MXenes are a novel class of 2D materials distinguished by their extensive structural and chemical diversity, making them highly promising for catalysis, energy storage, spintronics, and related applications[1]. Their tuneable surface chemistry is highly versatile, allowing for functionalization and precise control over their properties to meet specific application requirements. Previous studies using high-vacuum *in situ* TEM annealing and environmental TEM have provided atomic-scale insights into MXenes post-synthesis treatments, revealing routes to tailor their surface chemistry[2,3]. However, the direct response of MXenes to more complex environments resembling real-world processing and operational conditions remains unexplored using TEM methods. In this contribution, we present results on the evolution of Ti<sub>3</sub>C<sub>2</sub>T<sub>z</sub> MXene subjected to the inert and reactive atmospheric-pressure gas flows, investigated through a closed-cell TEM approach.

*In situ* experiments were performed using Linköping's double Cs-corrected FEI Titan<sup>3</sup> 60-300 TEM, equipped with a Protochips Atmosphere closed-cell TEM holder. Prior to drop-casting the MXene onto the SiN<sub>x</sub> membranes, the membranes were tailored by FIB milling to reduce their thickness, thereby enabling enhanced imaging quality. As-synthesized Ti<sub>3</sub>C<sub>2</sub>T<sub>z</sub> MXene sheets were thermally treated under various atmospheres, including inert (Ar), humid-inert (H<sub>2</sub>O/Ar), and reactive (H<sub>2</sub>/Ar and O<sub>2</sub>). Structural and chemical evolution of Ti<sub>3</sub>C<sub>2</sub>T<sub>z</sub> MXenes was monitored via HAADF-STEM imaging, SAED, and EELS fine structure analysis.

Figure 1 illustrates the evolution of Ti<sub>3</sub>C<sub>2</sub>T<sub>z</sub> MXene during *in situ* annealing flowing Ar. The sequence of plan-view HAADF-STEM overview images captures the progressive morphological changes that occur throughout the thermal treatment.

During treatment, Ti<sub>3</sub>C<sub>2</sub>T<sub>z</sub> sheets remained stable up to 450 °C but exhibited gradual structural decomposition beginning at 500 °C, leading to the formation of titanium oxide (TiO<sub>2</sub>) phase. The evolution at 450 °C temperature was investigated in a time sequence to examine potential surface changes prior to the structural decomposition. Within this range, it was observed that the Ti<sub>3</sub>C<sub>2</sub>T<sub>z</sub> surfaces undergo a fluorine-to-oxygen termination exchange while preserving the core Ti<sub>3</sub>C<sub>2</sub>T<sub>z</sub> structure (data not shown). This process is driven primary by the trace water (in Ar gas) mediated hydrolysis of Ti-F bonds through dissociative adsorption onto the surfaces. Our results highlight the extreme sensitivity of MXene surfaces to realistic environmental conditions, reveal the key role of trace species in driving termination evolution, and provide insights into post-treatment strategies for controlling MXene surface chemistry.

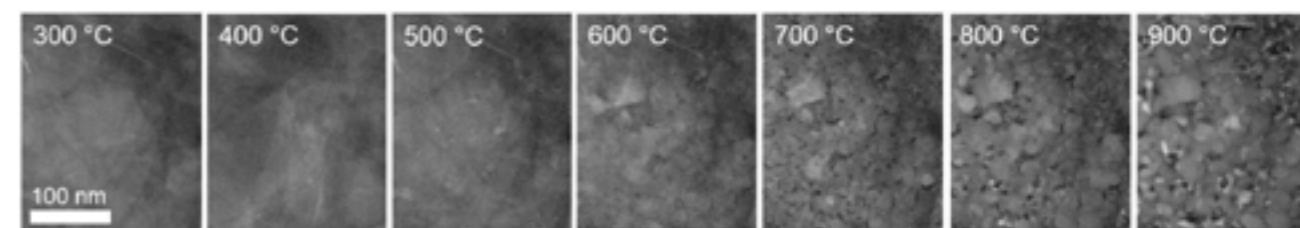


Figure 1: Plan-view HAADF-STEM images showing the evolution of Ti<sub>3</sub>C<sub>2</sub>T<sub>z</sub> MXene during *in situ* annealing under 1 bar of flowing Ar.

References:

[1] Naguib, M., et al., *Adv. Mater.* (2011) 23, 4248.

[2] Persson, I., *2D Mater.* (2017) 5, 015002.

[3] Persson, I., *Adv. Funct. Mater.* (2020), 30, 1909005.

# PRESENTATIONS

## From Operando Observation to Design Principles: Visualizing Dynamic Electrochemical Interfaces for Energy Technologies

Wang, X.<sup>1</sup>

<sup>1</sup>Technical University Berlin

Electrochemical energy technologies rely on dynamic solid–liquid interfaces that continuously restructure under applied bias, flow, and chemical gradients. Capturing these transient processes directly—and relating them to device performance—remains one of the central challenges in electrochemistry. In this presentation, I will demonstrate how operando electrochemical liquid-cell (S)TEM, enabled by Protochips *in situ* platforms, can be used to visualize and quantify interfacial evolution under realistic reaction conditions.

I will present an integrated operando workflow combining liquid-cell (S)TEM with complementary operando X-ray characterization and time-resolved online analytics. This approach allows nanoscale structural dynamics to be connected with measurable activity and durability metrics, translating real-time observations into predictive structure–activity–stability relationships. Rather than focusing on a single material system, the talk emphasizes transferable interfacial motifs across multiple electrochemical platforms, including high-rate CO<sub>2</sub> conversion in reactor-relevant environments, degradation pathways in fuel-cell materials, and electrochemically mediated CO<sub>2</sub> capture systems where coordination chemistry and waveform-dependent behaviors dominate performance.

Beyond mechanistic insights, this presentation aims to share practical considerations and experimental strategies for designing reliable operando liquid-cell experiments, highlighting lessons learned that may benefit the broader Protochips user community. By linking operando visualization to engineering-relevant metrics, this work illustrates how dynamic interface observation can guide actionable design principles for robust electrochemical technologies.