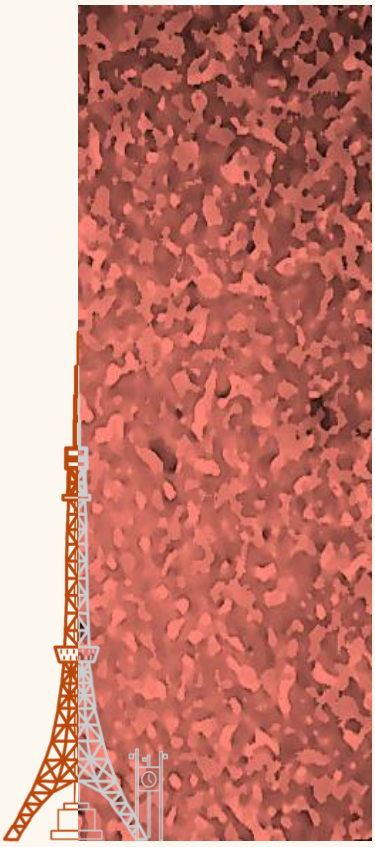
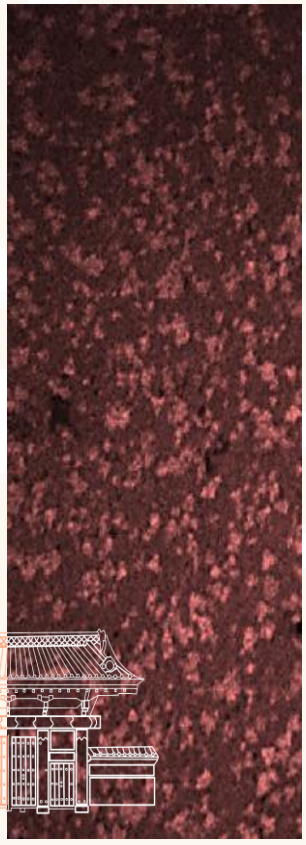
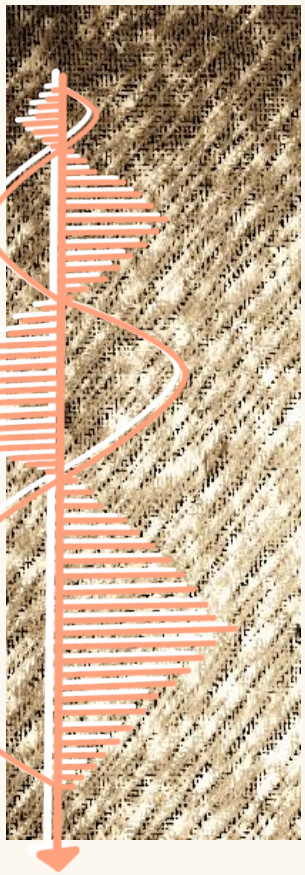
14 LEEMPEEM TOKYO 2026

LEEM PEEM14

14th Conference on Low-Energy & Photoemission Electron Microscopies







Abstract Book

October 5th ~ October 9th
Tokyo, Japan

Ito Hall
The University of Tokyo

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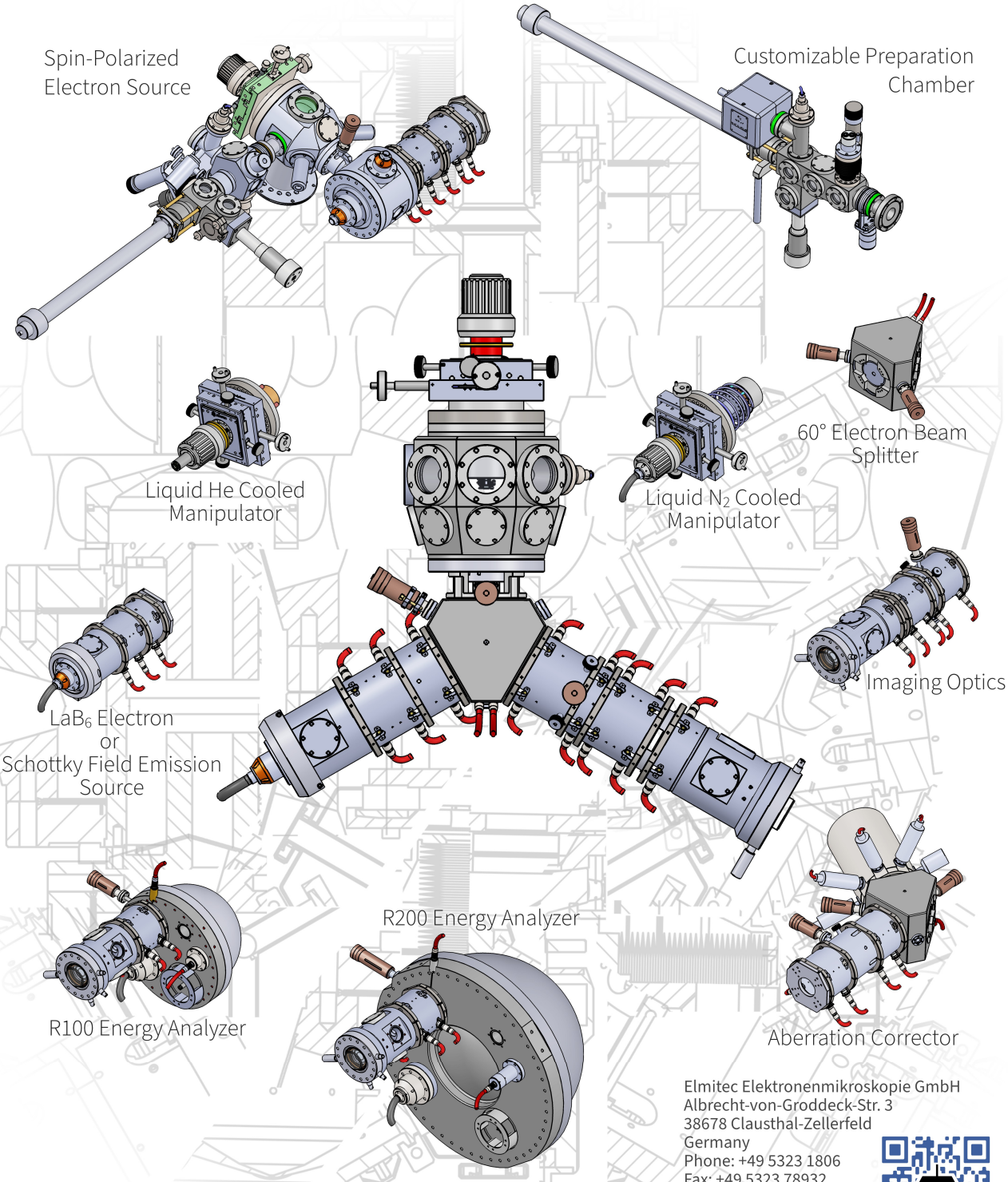
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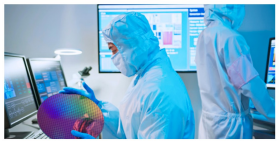
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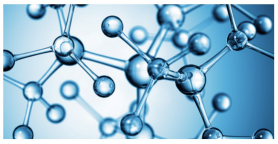
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11 eV

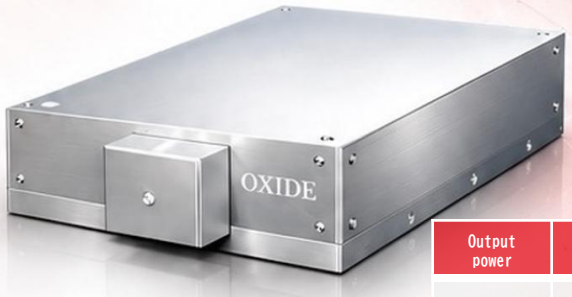
Energy resolution	Output power	Pulse bandwidth
≦ 0.6 meV	≧ 3 uW ≧ 5 uW	≦ 30 ps

Frequad-M

CW 266 nm

Deep-UV single frequency laser

- High power
- High stability
- Low noise
- Long life
- Excellent beam quality



4.7 eV
266 nm

Output power	Linewidth	Beam quality	Extinction ratio
0.3 W – 2 W	< 0.005 pm	TEMoo, M2 < 1.2	> 100 : 1

Frequad-W

CW 213 nm

Deep-UV single frequency laser

- Short wavelength
- High stability
- Low noise
- Long life
- High beam quality
- Air cooling



5.8 eV
213 nm

Output power	Linewidth	Beam quality	Extinction ratio
10 mW 20 mW	< 1MHz (0.15 fm)	TEMoo M2 < 2	> 100 : 1

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Program schedule (10/5-10/7)

	Oct.5 (Mon.)	Oct.6 (Tue.)		Oct.7 (Wed.)	
09:00-09:15		**Welcome Remark**		**Distiguished guest lecture** Electromagnetic Field Observations by High-Voltage Electron Holography	**Tanigaki, Toshiaki**
09:15-09:30		**Distiguished guest lecture** Attosecond Electron Microscopy	**Hassan, Mohammed**		
09:30-09:45					
09:45-10:00				«All-in-one» Setup for Photoelectron Microscopy	**Tkach, Olena**
10:00-10:15		Trans-switching in layered ferroelectrics: an XMLD study	**Achinuq, Barat**	Development of a Picosecond Spin-Polarized Electron Beam for Pump-Probe Spectroscopy in the QSPLEEM	**Choudhry, Usama**
10:15-10:30		Low-Energy Time-of-Flight Electron Characterization of 2D Materials	**Konvalina, Ivo**	Imaging Spin Filter for NanoESCA: from proven scattering targets towards full vectorial spin detection	**Patt, Marten**
10:30-10:45		Imaging material-defined optical nanogating landscapes in quasi-one-dimensional Bi4Br4	**Xian, Guoyu**	**Break**	
10:45-11:00		**Break**			
11:00-11:15				Exchange-coupled domains in NiO/Fe3O4(001) across the Verwey transition visualized by XMCD- and XMLD-PEEM	**Nita, Paweł**
11:15-11:30		Ultrafast dark-field momentum microscopy of electric field gated 2D semiconductors	**Bange, Jan Philipp**	Direct Observation of Chiral Magnon Splitting in Altermagnetic CrSb	**Lytvynenko, Yaryna**
11:30-11:45		Quasiparticle Interference Imaged by High-Resolution Photoemission Electron Microscopy at Low Temperature	**Zheng, Changxi**	From Interfacial Chirality to Complex Spin Textures with Spin-Polarized Low-Energy Electron Microscopy	**Chen, Gong**
11:45-12:00		Epitaxial Moiré-Graphene for resonance excitonic energy exchange in Moiré -Graphene-TMDC heterostructures	**Al-Mahboob, Abdullah**	Nd2SrFe2O7: a layered antiferromagnetic perovskite with a twist	**Maccherozzi, Francesco**
12:00-12:15		Real-time LEEM/LEED visualization of graphene nanoribbon and nanoporous graphene formation on Au(111)	**Procházka, Pavel**	Engineering magnetism in two-dimensional magnets	**Duan, Hengli**
12:15-12:30		Subsurface Carbon Incorporation Controls Graphene Nucleation On Ir(111)	**Mohanty, Smruti Ranjan**	Emergent Magnetic Textures in Permalloy/Hematite Bilayers	**Rodriguez de la Fuente, Oscar**
12:30-12:45		**Lunch (incl. Technology Forum)**		**Group photo** **Lunch (incl. Technology Forum)**	
12:45-13:00					
13:00-13:15	**Registration**				
13:15-13:30					
13:30-13:45					
13:45-14:00					
14:00-14:15		**Distiguished guest lecture** External Stimuli-Responsive Multistate Magnetic Switching in a Molecule-Based Magnet	**Tokoro, Hiroko**	**Distiguished guest lecture** RF cavity–based ultrafast electron microscopy: generation of ultrashort electron pulses for time-resolved experiments at high repetition rates	**Borrelli, Simona**
14:15-14:30					
14:30-14:45	**Tutorial-1** ToF-PEEM and momentum microscopy **Schönhense, Gerd**				
14:45-15:00		Studying Real-Time Processes with Liquid-Cell ONEM	**Simsek, Esra**	Latent image and intrinsic inhomogeneity in resists visualized by laser-based photoemission electron microscopy	**Fujiwara, Hirokazu**
15:00-15:15		Nanosecond pulsing of time-gated electron mirrors in a multi-pass transmission electron microscope	**Reynolds, Joshua**	Defect Inspection in Wide Band Gap Power Devices	**Khaliq, Muhammad Waqas**
15:15-15:30	**Break**	Ultrafast photoelectron momentum streaking in PEEM: Access to femtosecond surface currents	**Huber, David**	Tracing charge carriers in organic molecular crystals using PEEM	**Naeimi, Moha**
15:30-15:45	**Tutorial-2** Magnetism in Focus: LEEM, XPEEM, and Related Techniques **Mandziak, Anna**	Observation of nanometric objects in Water by DUV Laser-PEEM	**Zeng, Yanquan**	LEEM/PEEM as versatile probe of functional materials for microelectronics	**Nemsak, Slavomir**
15:45-16:00		**Break**		**Break**	
16:00-16:15					
16:15-16:30	**Break**	Imaging of Curvature-Induced Magnetic States in 3D Nanostructures by XMCD- PEEM	**Ruiz-Gomez, Sandra**	Spatiotemporal Imaging of Current-induced Domain Wall Depinning	**Han, Dongxue**
16:30-16:45	**Tutorial-3** High-Harmonic-Generation (HHG) Light Sources for Photoelectron Spectroscopy and Microscopy **Madéo, Julien**	Surface Magnetization in Bulk Fe3GeTe2 Ferromagnet	**Sadowski, Jerzy T., Al-Mahboob, Abdullah**	Real-Space Imaging of Orbital Nematicity across the phase diagram of Ba1-xNaxFe2As2	**Xu, Zifan**
16:45-17:00		Magnetism in Magnetite: Temperature-Dependent Domain Structure of Fe3O4 Surfaces	**Mandziak, Anna**	Structural and Chemical Evolution of N-Enriched Fe(111) Surface during Near-Ambient-Pressure Ammonia Synthesis	**Hsueh, Jing-Wen**
17:00-17:15		Spin-Polarized LEED and ARRES on Fe_3O_4(001)	**de la Figuera, Juan**	**Poster Session**	
17:15-17:30		Using Momentum Microscopy as a Screening Tool for Many-Body Interactions in Electronic Band Structures	**Røst, Håkon Ivarssønn**		
17:30-17:45		Chirality and Unconventional Charge Ordering in Kagome Metal CsV3Sb5	**Fedchenko, Olena**		
17:45-18:00		Surface Fermi Arcs in a Chiral Magnet	**Chiu, Wei-Sheng**		
18:00-18:30	**Welcome Reception (Ito Hall)**				
18:30-					

Tutorial	**Oral presentation**	**Registration/Welcome/Close**	**Poster Session**
Distiguished guest lecture	**Student oral presentation**	**Break/Lunch**	**Banquet**

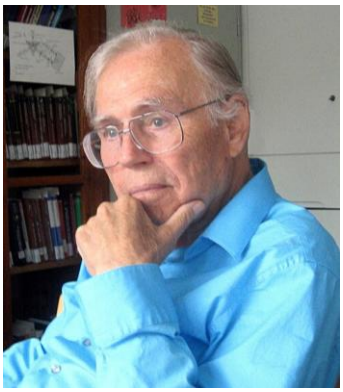
Program schedule (10/8-10/9)

	Oct.8 (Thu.)		Oct.9 (Fri.)	
09:00-09:15	**Distiguished guest lecture** Spin-on metal-oxide resists for high-NA EUV lithography: the challenges of printing and measuring the smallest resolution in high volume manufacturing	**Castellanos, Sonia**	**Distiguished guest lecture** Electrons Without Instructions: Agentic Workflows for the Next Era of Materials Characterization	**Spurgeon, Steven**
09:15-09:30				
09:30-09:45				
09:45-10:00	Virtual-Electrode LEEM for in-situ studies of Li and Na anode formation	**Kwiatek-Maroszek, Natalia**	Photoelectron Diffraction in the Minimum of the IMFP-Curve	**Schönhense, Gerd**
10:00-10:15	Measuring spherical and chromatic aberrations in Elmitec AC-SPELEEM	**Niu, Yuran**	Tritium Microscopy	**Asakura, Kiyotaka**
10:15-10:30	First μLEED-IV Adsorbate Structure Analysis Solely by LEEM-based Data: Se and Te on Ru(0001)	**Falta, Jens**	The QSPLEEM User Instrument: Time Resolved, Low Temperature, Angle Resolved Studies of Magnetic Quantum	**Stibor, Alexander**
10:30-10:45	**Break**		**Break**	
10:45-11:00				
11:00-11:15	Mixed or pure: F16CuPc and CoPc on Ag(100) surfaces	**Wagner, Thorsten**	Dynamic synthesis and characterization of large-area high-quality borophene on metal surfaces	**Wu, Rongting**
11:15-11:30	Near-edge absorption spectromicroscopy of ferroelectric BaTiO3(001)	**Teodorescu, Cristian Mihail**	Oxidation of single-layer antimonene	**Zdyb, Ryszard**
11:30-11:45	Templating defect arrays with moiré ferroelectricity in twisted hexagonal boron nitride	**Hawecker, Jacques**	**Closing Remark**	
11:45-12:00	Growth dynamics and chemical reactivity in Sm-doped cerium oxide inverse catalytic model systems	**Jan Ingo Flege**		
12:00-12:15	Spatiotemporal imaging of charge transfer in photocatalyst particles with energy- and time-resolved photoemission electron microscopy	**Chen, Ruotian**		
12:15-12:30	4D-SEM for Spatiotemporal Imaging of Charge Carriers in Photocatalysis: From Femtoseconds to Steady-State	**Zhao, Jianfeng**		
12:30-12:45	**Lunch**			
12:45-13:00				
13:00-13:15				
13:15-13:30				
13:30-13:45				
13:45-14:00	Coherent Band Engineering in a Bimetallic 2D Metal-Organic Framework	**Grisan Qiu, Yan Yan**		
14:00-14:15	Control of rotation and twist in bilayer graphene using novel faceted Cu growth substrates	**Cui, Zhenhao**		
14:15-14:30	Rise and fall of 1T-TaS2: Epitaxial growth of monolayer TaS2 on Au(111)	**Buß, Lars**		
14:30-14:45	Micro-ARPES visualization of strain-induced metallic state in 1T-TaS_2	**Suzuki, Shuto**		
14:45-15:00	Real-space visualization of conductive holes in organic transistors by operando photoemission electron microscopy	**Yoshikawa, Kosuke**		
15:00-15:15	Thermionic emission and Work Function modulation on BaWO4	**Gutiérrez Cuesta, Clara**		
15:15-15:30	**Break**			
15:30-15:45				
15:45-16:00	Probing Hyperbolic Plasmon Polaritons and Resonances in MoOCl2 by TR-PEEM	**Li, Yaolong**		
16:00-16:15	Nano-atto Imaging of Spatiotemporal Plasmonic Vortices on Chip	**Dai, Yanan**		
16:15-16:30	PEEM based near-field imaging of plasmonic topological nanochains	**Yan, Qiuchen**		
16:30-16:45	Linking extended vector wave fields with momentum space topology	**Meyer zu Heringdorf, Frank**		
16:45-17:00	**Scenic Walk to the Banquet Venue**			
17:00-17:15				
17:15-17:30				
17:30-17:45				
17:45-18:00				
18:00~	**Banquet**			

Tutorial
Distiguished guest lecture
Oral presentation
Student oral presentation
Registration/Welcome/Close
Break/Lunch
Poster Session
Banquet

Ernst Bauer Student Presentation Awards

Prof. Ernst G. Bauer



Professor Ernst G. Bauer is a pioneering scientist in surface physics, thin-film science, and electron microscopy. He received his Ph.D. in Physics from Ludwig Maximilian University of Munich in 1955 and later held leading research and academic positions in the United States and Germany, including at the Technical University of Clausthal and Arizona State University.

In 1958, Professor Bauer introduced the widely adopted classification of thin-film growth modes: Frank–van der Merwe, Volmer-Weber, and Stranski-Krastanov growth. He later proposed Low Energy Electron Microscopy (LEEM) in 1962 and pioneered further developments, including SPLEEM and SPELEEM, greatly expanding nanoscale surface imaging and characterization.

With more than 470 scientific publications and numerous international awards, his contributions have had a lasting impact on surface science, electron microscopy, semiconductor research, catalysis, and advanced materials characterization.

Student presentation awards

To support and recognize the talented young researchers in our field, we are thrilled to announce the establishment of the Ernst Bauer Student Presentation Awards. Named in honor of Professor Ernst Bauer, the pioneer of our community, these awards aim to spotlight outstanding research by the next generation of scientists.

Thanks to the generous support of SPECS Surface Nano Analysis GmbH and Elmitec GmbH, a cash prize of 1,000 EUR each will be awarded for the best student Oral Presentation and Poster Presentation.

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Instructions for the venue

The University of Tokyo (Hongo Campus)

Established in 1877, the University of Tokyo is Japan's oldest and most prestigious university. The Hongo Campus is renowned for its beautiful landscape, featuring iconic landmarks such as the Akamon (Red Gate) and Sanshiro Pond, and offering a serene, historic academic atmosphere in the heart of Tokyo.



Access to Hongo Campus

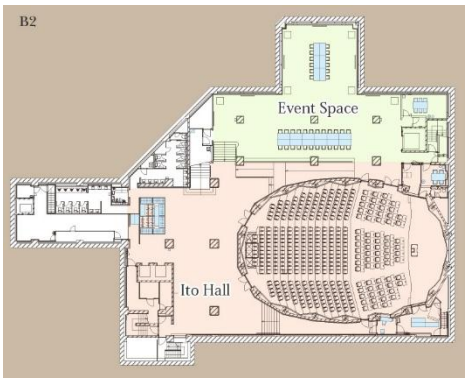
The campus is conveniently located with easy access via multiple subway lines:

Hongo-sanchome Station: (Marunouchi Line / Oedo Line) – 5-8 min walk.

Todaimae Station: (Namboku Line) – 10 min walk.

Yushima Station (Chiyoda Line) – 10 min walk.





Conference Site: Ito Hall

LEEM/PEEM-14 will be held at the Ito Hall, a facility designed for international academic exchange.

Address: 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan.

Banquet information

The conference banquet will be held at **Ueno Seiyoken**, a historic Western-style restaurant (Yōshoku) founded in 1876, located inside Ueno Park in Tokyo.

Start	18:00
Venue	Ueno Seiyoken
Adress	4-58 Uenokoen, Taito-ku, Tokyo 110-8715

Google map

How to reach the banquet venue

1. Conference walk - Scenic Walk to the Banquet Venue (approx. 40 min)

After the last session on Thursday, we will walk together to the banquet venue, passing through the Hongo Campus, including the iconic Yasuda Auditorium, and then through Ueno Park. Enjoy a short scenic walk through two of Tokyo's historic and cultural landmarks on the way to the banquet.

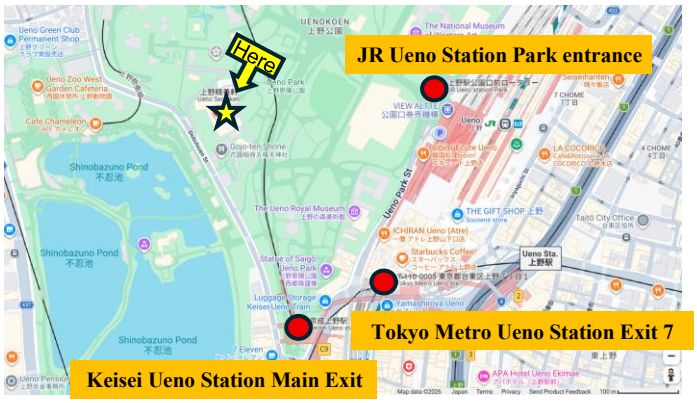






2. Getting There on Your Own

If you prefer to make your own way to the banquet venue, you can take the subway (Ueno Seiyoken is approximately a 5-minute walk from each subway station exit), a taxi, or Uber.





Tutorials

Tutorial-1

(Oct. 5, 14:30~15:15)

ToF-PEEM and momentum microscopy

Gerd Schönhense

Johannes Gutenberg Univ. of Mainz, Institute of Physics, Staudingerweg7, 55128 Mainz, Germany

This tutorial will introduce the concept of time-of-flight (ToF) recording in both real-space and k-space imaging. Recording the arrival time of imaged electrons as a third coordinate enables the simultaneous capture of energy bands up to several eV wide. Three-dimensional image recording enhances detection efficiency in X-PEEM and momentum microscopy (MM) modes. Almost all high-performance photon sources are pulsed, which has fuelled the dissemination of the ToF method. In PEEM, the recorded (x,y,Ekin) data arrays allow us to scroll through the spectral structure of the observed objects without scanning. In XPEEM, this provides direct access to chemical shifts across deposited thin flakes. In pump-probe experiments, the ToF-MM approach allows the simultaneous observation of the ultrafast dynamics of hole states (some eV below EF) and excited states (some eV above EF). Resolving the arrival-time coordinate opens up a way of circumventing the preconditions of Scherzer's theorem. Chromatic aberration can be easily corrected by numerically re-scaling the time slices.

The intrinsic obstacles of ToF-PEEM and ToF-MM will also be discussed. The recording efficiency is essentially limited by the current generation of detectors. Delay-line detectors typically record only one electron per excitation pulse. While two or three events can be resolved with extensive data processing, this is impossible at the high frame rates required for adjustment. This shortcoming poses a significant challenge in experiments at FELs, which are characterized by relatively low pulse rates. A second problem inherent to all cathode-lens instruments is the space-charge problem. If the total number of electrons (integrated over the full spectrum) becomes too large, the Coulomb interaction of the electrons becomes significant, which is detrimental to the energy and momentum resolution.

There is fascinating progress on the horizon. The development of pixelated solid-state detectors (e.g. the TimePix4) will solve the multi-hit problem once and for all, and will be a 'game changer'. The development of the multi-mode objective lens is intended to reduce space-charge interaction and mitigate the risk of field emission or sparking at high electric field strengths on the sample surface. Initial results from time-resolved electron diffraction in transmission mode pave the way for ultrafast diffraction to be implemented as a new operating mode in time-of-flight (ToF) microscopes. In addition to ultrafast band structure mapping, this will enable the tracking of related atomic motion.

Tutorial-2

(Oct. 5, 15:30~16:15)

Magnetism in Focus: LEEM, XPEEM and related techniques

Anna Mandziak

National Synchrotron Radiation Center SOLARIS, Czerwone Maki 98, 30392 Cracow, POLAND

Magnetic phenomena in low-dimensional and nanoscale systems are central to modern research in spintronics, quantum materials, and data storage technologies. Their investigation requires advanced imaging techniques capable of providing high spatial, temporal, and chemical sensitivity.

This tutorial introduces the principles and applications of Low Energy Electron Microscopy (LEEM), X-ray Photoemission Electron Microscopy (XPEEM), and Spin-Polarized Low Energy Electron Microscopy (SPLEEM). These methods enable direct visualization of structural, electronic, and magnetic properties of surfaces and thin films. Emphasis will be placed on magnetic contrast mechanisms, surface and interface sensitivity, and the ability to correlate structural, electronic, and magnetic information. Selected examples will illustrate how LEEM- and PEEM-based techniques are used to study magnetic domains, spin textures, ultrathin films, and dynamic processes in complex material systems.

The session aims to provide participants with both a conceptual understanding of these techniques and practical insight into their capabilities, limitations, and future developments.

Tutorial-3

(Oct. 5, 16:30~17:15)

Table-top XUV light sources for Photoemission Spectroscopy and Microscopy

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The capabilities of ARPES and PEEM are ultimately limited by the properties of available photon sources including photon energy, bandwidth, repetition rate, pulse duration, and brightness. This tutorial will briefly retrace how table-top sources have evolved to meet these photoemission needs, starting from low-order nonlinear UV sources in crystals and gases and focusing on XUV sources based on High-Harmonic Generation (HHG). With an initial demonstration in the 1990s, the properties of HHG sources have steadily advanced with the technological progress of femtosecond lasers and harmonic selection methods, now enabling table-top ARPES across the full Brillouin zone and the capability to perform time-resolved measurements. Recently, mitigating space-charge effects drove a shift from conventional kHz Ti:Sa drivers to MHz repetition rate HHG based on Yb and fiber lasers and enhancement cavities, which have unlocked multiple breakthroughs in condensed matter or molecular systems. After introducing the physics of HHG—the three-step model, cutoff scaling and phase matching—I will discuss practical implementation, scaling laws and the trade-offs between photon energy, flux, energy and temporal resolution, and repetition rate. I will close on recent strategies developed in our group that achieve state-of-the-art conversion efficiency using a sub-μJ MHz NIR driver, broadening the applicability of table-top XUV sources.

Oral Presentation

Distinguished Guest Lectures

Date	Time	Title	Lecturer
Oct. 6	09:15~10:00	Attosecond Electron Microscopy	Hassan, Mohammed
Oct. 6	14:00~14:45	External Stimuli-Responsive Multistate Magnetic Switching in a Molecule-Based Magnet	Tokoro, Hiroko
Oct. 7	09:00~09:45	Electromagnetic Field Observations by High-Voltage Electron Holography	Tanigaki, Toshiaki
Oct. 7	14:00~14:45	RF cavity–based ultrafast electron microscopy: generation of ultrashort electron pulses for time-resolved experiments at high repetition rate	Borrelli, Simona
Oct. 8	09:00~09:45	Spin-on metal-oxide resists for high-NA EUV lithography: the challenges of printing and measuring the smallest resolution in high volume manufacturing	Castellanos, Sonia
Oct. 9	09:00~09:45	Electrons Without Instructions: Agentic Workflows for the Next Era of Materials Characterization	Spurgeon, Steven

Tu-AM-01

Trans-switching in layered ferroelectrics: an XMLD study

Barat Achinuq[1], Pushpendra Gupta[2], Sergio Puebla[2], Xinyan Li[3], Sajid Husain[2], Matthew Chen[2], Yogesh Kumar[1], Ashish Omar[2], Alpha N'Diaye[1], Christoph Klewe[1], Sujoy Roy[1], Ramamoorthy Ramesh[2,4]

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Ferroelectric materials exhibit a spontaneous electric polarization central to non-volatile memories, sensors, and actuators. While conventional switching relies on fields parallel to the polarization vector, achieving controlled manipulation of the in-plane polarization component using an out-of-plane electric field remains a long-standing challenge. In this work, we demonstrate that a trilinear coupling between orthogonal polarization components—mediated by oxygen-octahedral distortions in layered monoclinic $Bi_4Ti_3O_{12}$ (BTO) thin films—enables such "trans-switching." To elucidate this mechanism as a function of film thickness, we conduct X-ray linear dichroism (XMLD) studies using X-ray photoemission electron microscopy (XPEEM) and X-ray absorption spectroscopy (XAS). By probing the Ti L-edges, we directly correlate the local electronic and crystal symmetry changes in the absorption spectra with the specific ferroelectric polarization states of the films. Our results provide direct evidence that the large in-plane polarization switches deterministically under an out-of-plane electric field. This cross-coupling provides a powerful route for the transverse manipulation of ferroic order and establishes layered ferroelectrics as a platform for capacitive computing concepts, analogous to the transconductance of modern CMOS electronics.

Tu-AM-02

Low-Energy Time-of-Flight Electron Characterization of 2D Materials

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Two-dimensional (2D) materials exhibit electronic properties and collective excitations that are highly sensitive to surface chemistry and thickness, requiring the use of surface-sensitive characterization techniques. In this work, graphene, h-BN, MoS_2, and Ti_3C_2 MXene were investigated using an advanced scanning low-energy electron microscopy system combined with time-of-flight spectroscopy (SLEEM/ToF) [1]. This approach enables the acquisition of low-energy electron energy-loss spectra (EELS) with enhanced surface sensitivity and reduced beam-induced damage.

The obtained EELS spectra provided information on plasmon excitations in the studied materials and demonstrated the potential of SLEEM/ToF for probing the electronic structure of 2D systems [2]. In addition, the inelastic mean free path (IMFP) of electrons in graphene was quantitatively determined in the 10–50 eV energy range, yielding a value of 1.6 ± 0.3 nm. The results confirm that SLEEM/ToF is a promising tool for the surface-sensitive investigation of two-dimensional materials and provides valuable experimental data [3].

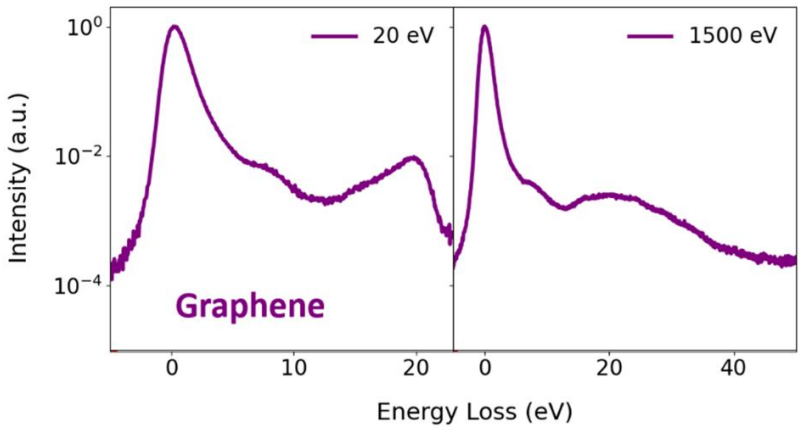


Fig 1. Low-energy EELS spectra of graphene acquired at landing energies of 20 eV and 1500 eV. The spectra exhibit a pronounced zero-loss peak, characteristic plasmon peaks, and a secondary-electron peak, which shifts toward higher energy losses with increasing landing energy.

References

[1] Konvalina I. et al., *Nanomaterials*, **11**, 2435 (2021).
[2] Paták A. et al., *Physical Review B*, **111**, 125113 (2025).
[3] Pizúrová et al., *Nanomaterials*, **16**, 501 (2026).
[4] This research was supported by the Technology Agency of the Czech Republic under grants No. TN02000020 and TQ28000004, and by institutional support under project RVO:68081731. With support of Strategy AV21, program Breakthrough Technologies for the Future – Sensing, Digitisation, Artificial Intelligence and Quantum Technologies.

Tu-AM-03

Imaging material-defined optical nanogating landscapes in quasi-one-dimensional Bi_4Br_4

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Electrostatic potential is a key control parameter for quantum materials, yet combining nanoscale spatial definition with ultrafast optical operation remains challenging [1-3]. Here, we show that quasi-one-dimensional Bi4Br4 converts nominally uniform femtosecond excitation into a material-defined optical nanogating landscape. Using multidimensional photoemission electron microscopy (PEEM), we directly image local photoinduced potentials across individual flakes. Pixel-resolved spectra reveal pump-induced rigid energy shifts that correspond to gate-equivalent photovoltages approaching 80 mV. The response is strongly enhanced near flake boundaries compared with the terrace interior, indicating facet-dependent band unbending under identical excitation. Energy- and momentum-resolved PEEM further separates terrace-dominated and boundary-sensitive photoemission channels with distinct fingerprints. The boundary-to-terrace photovoltage evolution is continuous and is captured by a minimal electrostatic relaxation model. Our results establish photovoltage as a deep-subwavelength observable and reveal an all-optical electrostatic control mechanism in which intrinsic electronic texture transforms uniform light into nanogating landscapes.

Reference(s)

[1] K. S. Novoselov *et al.*, *Science*, **306**, 666-669 (2004).
[2] L. A. Cohen *et al.*, *Nature Physics*, **19**, 1502-1508 (2023).
[3] A. L. Yeats *et al.*, *Science Advances*, **1**, e1500640 (2015).

Tu-AM-04

Ultrafast dark-field momentum microscopy of electric field gated 2D semiconductors

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Two-dimensional (2D) semiconductors and moiré materials, formed by stacking and twisting atomically thin layers, provide an exciting platform to discover and engineer new quantum states. Precise and reversible control of carrier density and many-body effects is readily achieved through in-situ electric field gating. In combination with angle-resolved photoemission spectroscopy this has been a powerful probe of the static electronic band structure [1]. However, capturing the ultrafast dynamics of excited states in gated 2D materials, including hybrid excitons [2], interlayer excitons [3, 4], and trions [5], remains a fundamental challenge due to the limited real-space resolution of ultrafast time- and momentum-resolved spectroscopy techniques.

In this contribution, I will present how time-resolved momentum microscopy combined with dark-field imaging techniques provides direct access to both the energy landscape and femtosecond dynamics of bright and dark excitons at nanometer length scales [6]. This methodology enables the disentanglement of electron and hole transfer pathways across twisted transition metal dichalcogenide interfaces and reveals the ultrafast formation of quasiparticles as a function of gate voltage.

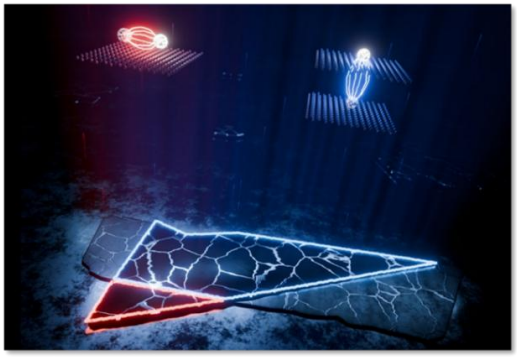


Fig 1. An artistic view of ultrafast, order-selective imaging of dark intra- and interlayer exciton formation at the nanoscale.

Reference(s)

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[2] J. P. Bange et al. *Science Advances*, **10**, eadi1323 (2024).
[3] D. Schmitt et al. *Nature*, **608**, 499 (2022).
[4] D. Schmitt et al. *Nature Photonics*, **19**, 187 (2025).
[5] G. Meneghini et al. *Nano Letters*, **26**, 5866 (2026).
[6] J. P. Bange et al. *arXiv.2608.18925* (2026).

Tu-AM-05

Quasiparticle Interference Imaged by High-Resolution Photoemission Electron Microscopy at Low Temperature

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High-resolution imaging of low-temperature quantum phenomena is of paramount importance; however, so far only scanning tunneling microscopy (STM) has been capable, leaving many crucial issues—such as electronic phase transition dynamics and ultrafast decoherence—unobservable. Here we report the possible observation of quasiparticle interference (QPI) using low-temperature photoemission electron microscopy (LT-PEEM) on graphene/Cu(111). Although the intrinsic QPI wavelength (~1.5-3 nm) is below our 4.4 nm resolution, a distinct dark stripe at atomic steps is detected (Fig 1) [1]. Contrast transfer function (CTF) modeling confirms this stripe as the convoluted signature of QPI-induced local density of states (LDOS) modulations, validated by in situ angle-resolved photoemission spectroscopy (ARPES). Our work establishes PEEM as a viable tool for QPI studies, enabling time- and momentum-resolved imaging of electronic dynamics in quantum materials.

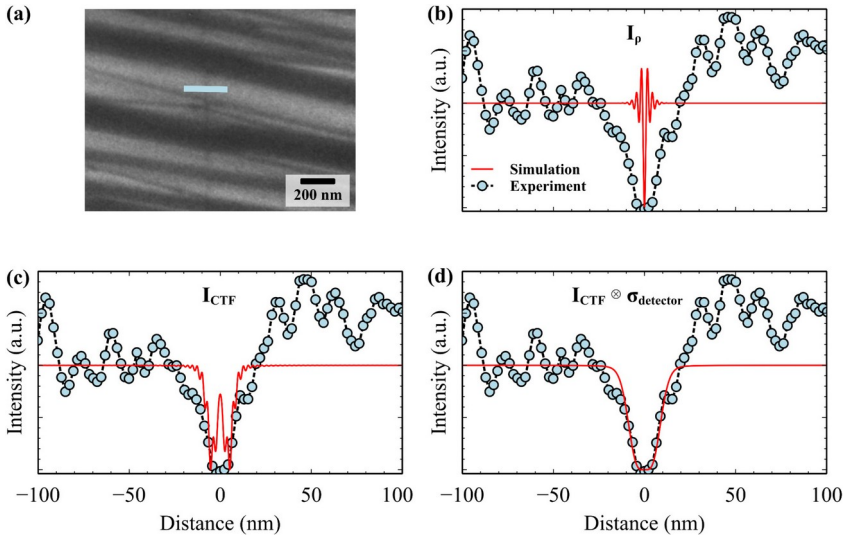


Fig 1. Analysis of the QPI intensity profile in LT-PEEM. (a) Zoomed-in LT-PEEM image of the graphene/Cu(111) surface, showing a single atomic step. (b)–(d) Comparison between the experimental QPI intensity profile (light-blue dots) obtained along the light-blue line in (a) and (b) the numerical QPI profile, (c) the CTF-calculated profile, and (d) the CTF-calculated profile considering detector blurring, respectively [1].

Reference

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Tu-AM-06

Epitaxial Moiré-Graphene for resonance excitonic energy exchange in Moiré -Graphene-TMDC heterostructures

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Two-dimensional (2D) quantum materials, specifically, Moiré-Graphene (MGr) and van der Waals heterostructures (HSs) of quantum materials have attracted great interest because of their exotic quantum properties and having promises in novel optoelectronic and photonic applications. HSs made of stacking atomically thin layers of transition-metal dichalcogenides (TMDCs) allow to manipulate the optical and spintronic properties. In TMDC HSs of monolayers having the resonance between dark excitonic states, we observed unconventional energy transfer (ET) process [1] massively enhancing photoluminescence (PL) [1,2] and valley polarization (VP) [2].

Common practice of realization of Moiré graphene is done upon creating twists of exact magic angles between two layers of graphene, controlling of which at reasonable length-scale is poor. In the present work, we synthesized epitaxial MGr (EMGr) in-situ, low-energy electron microscope and X-ray photoemission electron microscope (LEEM/XPEEM), obtained Moiré-electronic band structure employing high-resolution ARPES and fabricated HSs of WSe_2-hBN-EMGr in Ar-atmosphere.

While Moiré -LEED is found to be associated with point-on-point commensuration, Moiré ARPES is found to be associated with line-on-line commensuration. Alternately, spatial period of electronic-Moiré lattice is shorter than that of geometric-Moiré. More interestingly, the measured electronic band structure of EMGr is found to have resonance between the energy of optical transition from Moiré Dirac-cone to Van Hove Singularity states across M-point and excitation energies in WSe_2 resulting in unconventional dark excitonic energy exchange between EMGr and WSe_2.

Research was carried out at the Center for Functional Nanomaterials and the National Synchrotron Light Source II at Brookhaven National Laboratory under Contract No. DE-SC0012704.

Reference(s)

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Tu-AM-07

Real-time LEEM/LEED visualization of graphene nanoribbon and nanoporous graphene formation on Au(111)

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On-surface synthesis enables atomically precise fabrication of graphene nanoribbons (GNRs), which can be further coupled into extended nanoporous graphene (NPG) networks [1]. While STM and non-contact AFM provide atomic-scale information about the final products, they offer limited insight into the mesoscale structural evolution occurring during high-temperature synthesis.

Here, we employ low-energy electron microscopy (LEEM) and diffraction (LEED) to follow the formation of GNRs from diphenyl–10,10′-dibromo-9,9′-bianthracene (DP-DBBA) molecules and their subsequent coupling into NPG on Au(111). Distinct diffraction signatures are observed for precursor molecules, intermediate polymer chains, graphene nanoribbons, and the final nanoporous graphene network (Fig. 1). The ordering of these structures exhibits a clear correlation with the herringbone reconstruction of the Au(111) substrate.

Bright- and dark-field LEEM imaging further reveals the spatial distribution of ordered GNR and NPG domains with respect to terraces, step edges, and herringbone domains. The combination of LEEM and LEED thus provides direct insight into the structural evolution during on-surface synthesis and enables rapid optimization of growth conditions for large-area ordered nanoporous graphene.

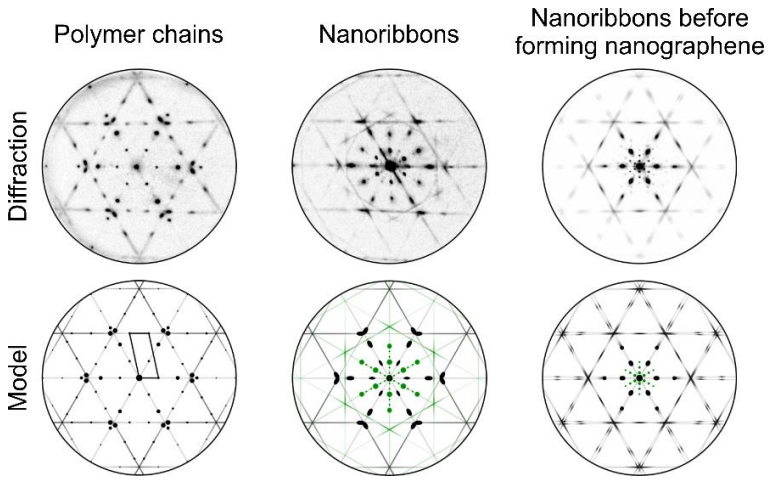


Fig 1. LEED patterns and corresponding models of polymer chains on Au(111), graphene nanoribbons, and graphene nanoribbons before nanoporous graphene formation.

Reference

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Tu-AM-08

Subsurface Carbon Incorporation Controls Graphene Nucleation On Ir(111)

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Graphene nucleation during CVD growth can be influenced by surface and bulk processes. While nucleation on surfaces is commonly described by adsorption, diffusion, and aggregation of adatoms, transition metal substrates introduce an additional pathway through dissolution of precursor atoms into the bulk [1]. Here, we investigate how this bulk dissolution influences the nucleation of graphene islands during growth on Ir(111), using low-energy electron microscopy. By systematically varying growth temperature and precursor dosing pressure, we observe a pronounced transition between two nucleation regimes [2]. At low dosing pressures, carbon loss into the substrate suppresses island formation, resulting in low nucleation densities. As the dosing pressure increases, the influence of bulk dissolution reduces, and nucleation becomes increasingly governed by surface processes, leading to substantially higher island densities. The measured scaling behavior can be understood within the framework of kinetic nucleation theory [2] and is reproduced by kinetic Monte Carlo simulations [3] that explicitly account for carbon dissolution in the bulk. The combined experimental and simulation results reveal a universal crossover in nucleation behavior and establish finite solubility as a key factor governing nucleation in two-dimensional material growth [4].

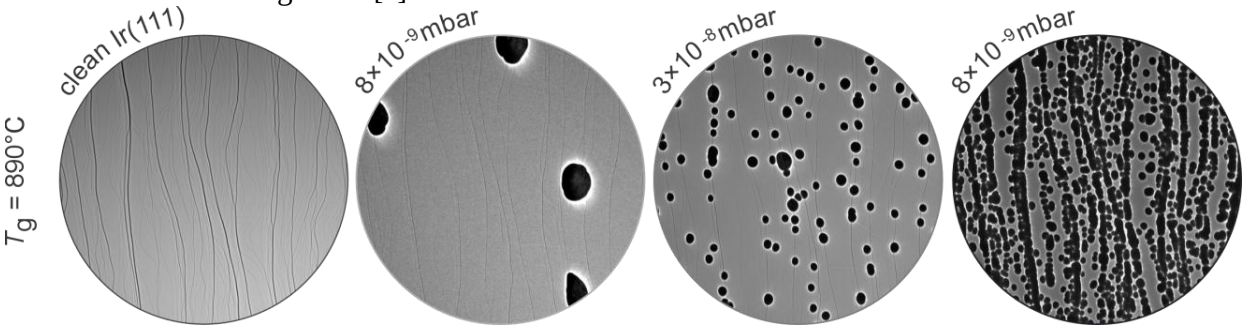


Figure: LEEM morphology showing variation in graphene island density on Ir(111) surface depending on the ethylene dosing pressure at the same growth temperature of 890°C. The field of view is 40 µm.

References:

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Tu-PM-01

Studying Real-Time Processes with Liquid-Cell ONEM

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We have developed Optical Near-Field Electron Microscopy (ONEM), a hybrid imaging technique that combines optical illumination with (photo)electron microscopy in a novel way [1].

ONEM utilises a straightforward principle: photoemission. A laser illuminates a sample from behind, and a low-work-function photocathode deposited on the sample surface converts the near-field optical response of any object within the sample into an electron flux, which is then imaged using electron optics. Because ONEM relies on near-field interactions, its theoretical resolution scales linearly with the separation between the sample surface and the photocathode [1]. Recently, we reached a 30 nm resolution using 405-nm light [2]. Furthermore, since sample thickness is not a limiting factor for imaging, ONEM allows one to use relatively thick liquid cells.

To highlight ONEM's potential in studying *real-time* physical, chemical or biological processes in liquid cells, we present two experiments [2]. First, we track the movement of living *Escherichia coli* bacteria in water. Next, we perform a three-electrode electrochemistry experiment in an acidic copper sulphate electrolyte. Through cyclic voltammetry scans, we investigate the growth dynamics of copper electrodeposition on a Pt working electrode in real time. For the latter experiment, a potentiostat has been integrated into the system.

These results introduce ONEM as a promising, damage-free candidate for high-resolution studies of processes in biological, electrochemical and other dynamic systems.

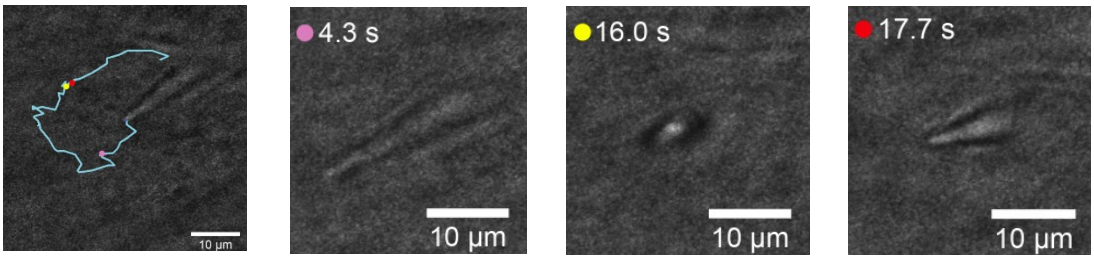


Fig 1. Real-time movement of Escherichia coli bacteria in water.

References

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Tu-PM-02

Nanosecond pulsing of time-gated electron mirrors in a multi-pass transmission electron microscope

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Beam-induced sample damage limits the absolute sensitivity and resolution of electron microscopy measurements for a large class of samples including novel battery materials and small biological molecules. When damage limits the total applicable electron dose to N electron-sample interactions, sequentially interacting the same N/m electrons with the sample m times enhances the measurement signal-to-noise ratio by $\sqrt{m}$ relative to a measurement performed with N independent electron-sample interactions [1,2]. Such a multi-pass measurement protocol saturates quantum limits on measurement sensitivity [3]. In a multi-pass transmission electron microscope, electrons are coupled into and out of a re-imaging electron optical system using time-gated electron mirrors [4]. Two-pass electron illumination is achieved with a continuous electron beam. The gated electron mirrors are used to switch on and off illumination on nanosecond timescales and can be pulsed synchronously with laser-triggered electron emission for routing and control of ultrafast electron pulses. We study the switching dynamics of the gated electron mirror system in a 10 keV multi-pass transmission electron microscope using laser-triggered femtosecond electron pulses, and we discuss pulse sequences and timing constraints for high-resolution multi-pass electron imaging at increasing numbers of passes through the microscope optics.

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Tu-PM-03

Ultrafast photoelectron momentum streaking in PEEM: Access to femtosecond surface currents

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The terahertz (THz) spectral range has emerged as a unique ground for probing and controlling interface phenomena, as low-energy collective excitations leave distinct fingerprints in this frequency window. The spintronic THz emitter (STE) addresses the increasing demand for compact THz sources: by harnessing ultrafast spin-to-charge conversion in magnetic heterostructures, it generates broadband THz radiation directly in the heavy metal layer. Crucially, while far-field THz spectroscopy has become well established, phase-resolved characterization of the near-field THz radiation at the emitting surface remains a largely open challenge – yet it is precisely this near-field that governs energy transfer, carrier dynamics, and coupling to surface excitations at the nanoscale. Here we introduce a technique that uniquely provides such phase-resolved near-field access through photoelectron momentum streaking. We generate an ultrafast charge current in a Fe(3 nm)/Pt(3 nm) bilayer grown on MgO(001) by backside pumping of the Fe layer with a femtosecond laser pulse (695 nm, 40 fs, 2.5 mJ/cm^2) focused down to a diameter of 15 µm. Electrons photoemitted by an additional UV laser on the front side are accelerated by the near-field component of the emerging THz field. Photoelectron momentum microscopy provides direct access to the momentum streaking and thereby to the electric near field component in vicinity of the surface. Simulations of ultrafast charge-current dynamics are in good agreement with the experimental data and confirm that, in the near-field regime, the emitted electric field is proportional to the charge current. Introducing a real-space selection, this technique enables imaging charge currents on the ultrafast timescale.

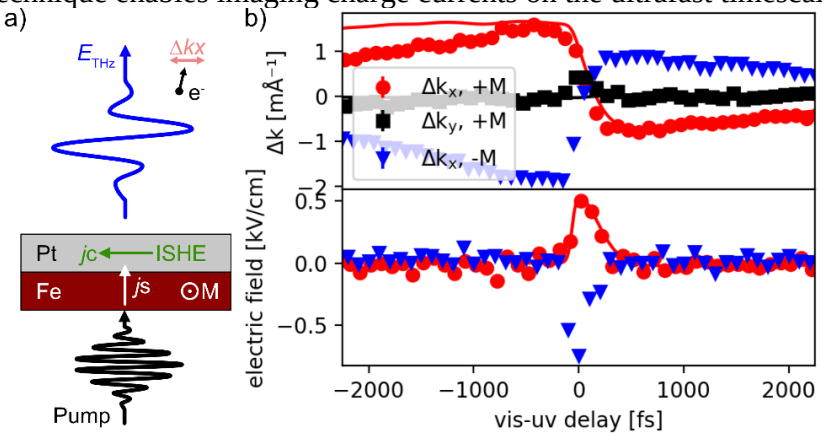


Fig 1. a) Schematic of the THz streaking experiment with backside pumping of the Pt/Fe bilayer. The spin current j_S (white) is converted into a charge current j_C (green) via the inverse spin Hall effect (ISHE) in the adjacent Pt layer. Photoemitted electrons at the top surface are accelerated by the emerging electric field E_{THz}, leading to a momentum shift Δk. b) Time-resolved momentum streaking Δk of photoemitted electrons for opposite magnetization directions (± M, red and green) in the Fe layer. The electric field is obtained from the exerted force via $\hbar\, d\mathbf{k}/dt = -e\mathbf{E}_{THz}$.

Tu-PM-04

Observation of nanometric objects in Water by DUV Laser-PEEM

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Photoemission electron microscopy (PEEM) is a promising technique for studying solid-liquid-gas interfaces[1]. Moreover, Deep-ultraviolet laser PEEM would have advantages for its low radiation damage and high resolution[2]. However, sealing an aqueous solution in ultra-high-vacuum and under high voltage, both required for high resolution PEEM, while ensuring the observation of a contrast remain an obstacle. In this work, we developed an aqueous DUV Laser-PEEM cell based on SiN_x membranes and achieved stable operation in UHV with a -20kV extraction field.

Using TiO_2 nanorods as a model structure, we systematically investigated charging behavior under 213 nm and 266 nm laser excitation. The results show that the TiO_2 nanorods modulate the local surface potential and generate distinct PEEM contrast, while the introduction of a water layer significantly reduces this local contrast. In addition, buried TiO_2 nanostructures retain detectable local electrostatic signatures even when immersed in water, demonstrating the capability of PEEM to probe buried dielectric objects under water.

These results demonstrate that charging is not a shortcoming in liquid PEEM but serving as a useful contrast mechanism for mapping electrostatic potential distributions at buried interfaces. The developed cell provides a broadly applicable approach for PEEM studies of liquid and other aqueous systems in various fields.

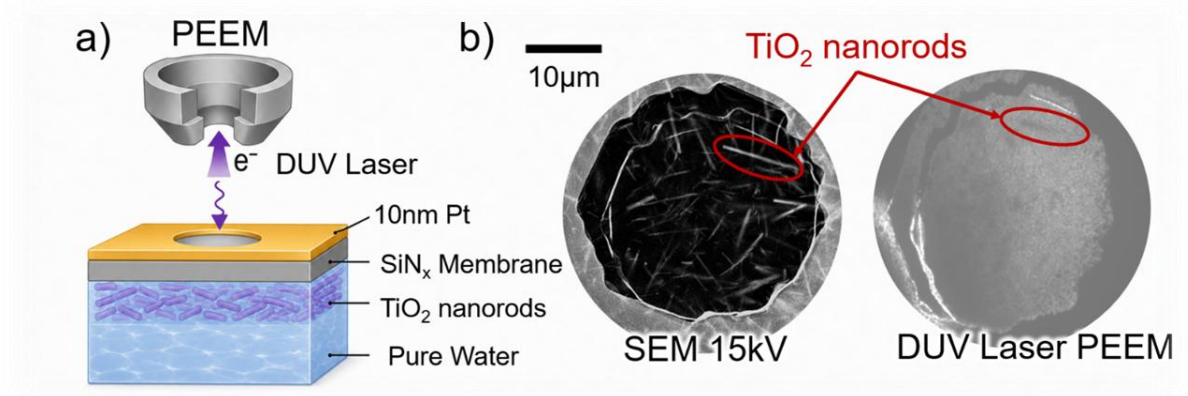


Fig 1. a) Schematic of the liquid DUV Laser-PEEM setup. b) Corresponding SEM and DUV Laser-PEEM images of TiO_2 nanorods immersed in water.

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Tu-PM-05

Imaging of Curvature-Induced Magnetic States in 3D Nanostructures by XMCD- PEEM

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Three-dimensional (3D) magnetic nanostructures provide a unique platform to explore curvature-driven spin textures. Recent advances in 3D nanoprinting using focused electron beam induced deposition (FEBID), which allows for high control over geometry, combined with electrodeposition, enable the realization of complex-shaped magnetic solids and nanotubes with well-defined geometry and topology. These architectures introduce curvature-induced effective fields that stabilize non-trivial magnetization configurations and enable geometrical control over their dynamics [1,2,3].

X-ray photoemission electron microscopy (X-PEEM), exploiting X-ray magnetic circular dichroism (XMCD) contrast, provides direct access to the local magnetization vector with high spatial resolution, making it particularly suitable for investigating such 3D systems. PEEM measurements, combined with in situ application of magnetic fields, allow not only the study of spin textures in these nanostructures, but also their dynamics, revealing the dominant role of curvature and geometry in defining the magnetic energy landscape.

These results demonstrate that geometry can be used as an effective control parameter for engineering magnetic states in 3D nanostructures. The ability to directly visualize and manipulate curvature-induced spin textures using PEEM provides a powerful approach to correlate geometrical design with magnetic functionality.

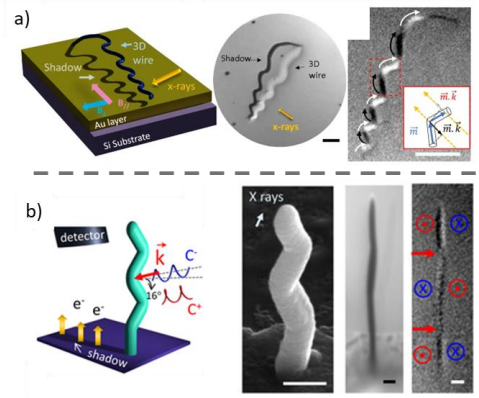


Fig 1. a) schematic together with the XAS and the XMCD image of a solid curve nanostructure. b) schematic together with the SEM, XAS and XMCD image of a tubular nanostructure.

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Tu-PM-06

Surface Magnetization in Bulk Fe_3GeTe_2 Ferromagnet

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We employ the XMCD imaging mode of X-ray photoemission electron microscopy (XMCD-XPEEM) to investigate the magnetic domain structure of Fe_3GeTe_2 in zero applied magnetic field. The observed domain configuration follows the expected pattern for thick crystals with strong uniaxial magnetic anisotropy.

To further probe the magnetic texture, we use low-energy electron microscopy (LEEM) with a tilted incident electron beam to image magnetic domain walls. Unlike spin-polarized LEEM, this method does not require specialized sample preparation or a spin-polarized electron source. Instead, magnetic contrast is generated by tilting the incident electron beam relative to the sample surface normal, or equivalently by tilting the sample itself. We demonstrate how the resulting contrast can be analyzed to determine the domain-wall type and to extract critical exponents associated with the surface magnetic behavior.

This work is supported by NSF Grant No. DMR-1809931. This research used resources of the Center for Functional Nanomaterials and the National Synchrotron Light Source II, which are U.S. Department of Energy (DOE) Office of Science facilities at Brookhaven National Laboratory, under Contract No. DE-SC0012704.

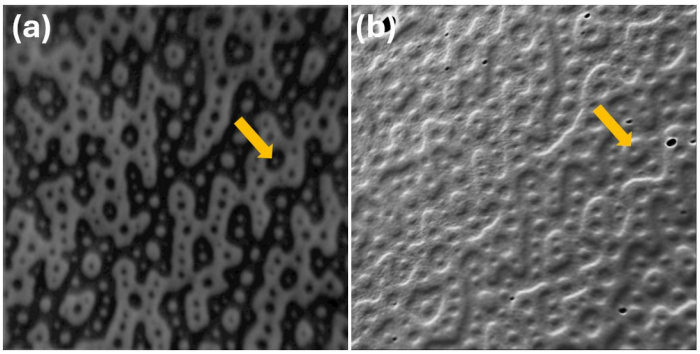


Fig. 1. (a) XMCD-PEEM image taken at 110 K. The dark and bright regions correspond to up and down magnetization orientation relative to the sample normal. XMCD images were taken at the peak of the Fe L3-edge spectrum. (b) A tilted-beam LEEM image of the same area as in (a) showing a surface magnetic contrast at domain walls.

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Tu-PM-07

Magnetism in Magnetite: Temperature-Dependent Domain Structure of Fe_3O_4 Surfaces

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Magnetite (Fe_3O_4) is a prototypical ferrimagnetic oxide with strong coupling between structural, electronic, and magnetic properties. At room temperature it crystallizes in a cubic inverse spinel structure and undergoes the Verwey transition at 115–125 K, involving a metal–insulator transition, structural distortion, and charge ordering that strongly affect its magnetic behavior [1].

We investigate the magnetic domain structure of Fe_3O_4 single crystals with (100), (110), and (111) surface orientations at room and low temperatures using LEEM, XPEEM, and XMCD-PEEM. Surfaces were prepared by Ar^+ sputtering and annealing under ultra-high vacuum conditions and characterized by LEED [1].

XMCD-PEEM measurements reveal a strong dependence of domain configurations on crystallographic orientation. The observed magnetization directions correspond to projections of the bulk ⟨111⟩ easy axes onto the surface plane when no easy axis lies within it, as for the (100) and (111) surfaces. Across the Verwey transition [2], changes in domain morphology are observed, although increased complexity is not universal: the (100) surface shows simpler domain patterns at low temperature, consistent with the appearance of in-plane easy axes, while the (110) surface exhibits more complex behavior.

These results demonstrate the key role of surface orientation in determining magnetic domain structures in Fe_3O_4 and their evolution across the Verwey transition.

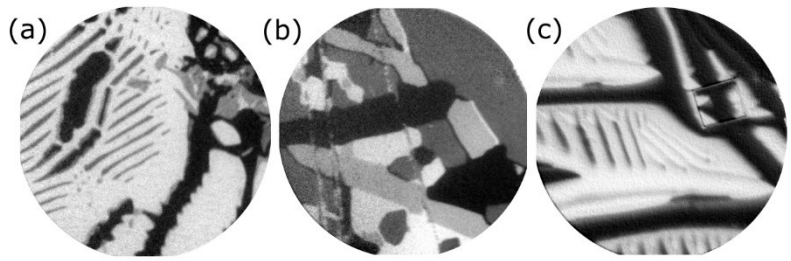


Fig. 1. XMCD-PEEM images of different magnetite surfaces: (a) (001), (b) (110), and (c) (111).

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Tu-PM-08

Spin-Polarized LEED and ARRES on $Fe_3O_4(001)$

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Magnetite (Fe_3O_4) is a canonical half-metal and ferrimagnet of long-standing interest for spintronics, yet the spin-dependent electronic structure of its (001) surface remains poorly characterized experimentally. We present spin-polarized LEED I(V) and Angle-Resolved Reflection Electron Spectroscopy (ARRES [1]) measurements on the $Fe_3O_4(001)$ surface, to our knowledge the first spin-resolved LEED diffraction and spin-resolved ARRES on a ferrimagnetic oxide.

The $(\sqrt{2}\times\sqrt{2})R45°$ reconstructed surface [2] shows a striking contrast between integer-order and reconstruction beams: the four first-order beams display comparable spin-asymmetry, while the superstructure spots show no detectable spin-asymmetry. The equal sign of the spin-assymetry on all four first-order beams is consistent with exchange scattering from the ferrimagnetic order as the dominant mechanism, since spin-orbit scattering would produce sign changes between opposite beams at normal incidence. The null result on the reconstruction beams may reflect the suppressed spin polarization of the Fe^{3+}-dominated SubSurface-Cation-Vacancy model of the reconstructed surface [2-4]. ARRES maps the spin-resolved reflectivity as a function of kinetic energy (0–25 eV) and parallel momentum along high-symmetry directions of the surface Brillouin zone. The X–Γ–M composite map reveals clear band-like features in the unoccupied electronic structure. The spin asymmetry reaches ~10% near 8 eV at Γ, with a sign change around 15–17 eV, consistent across both measured directions (Γ–X and Γ–M), confirming the signal is intrinsic to the ferrimagnetic order.

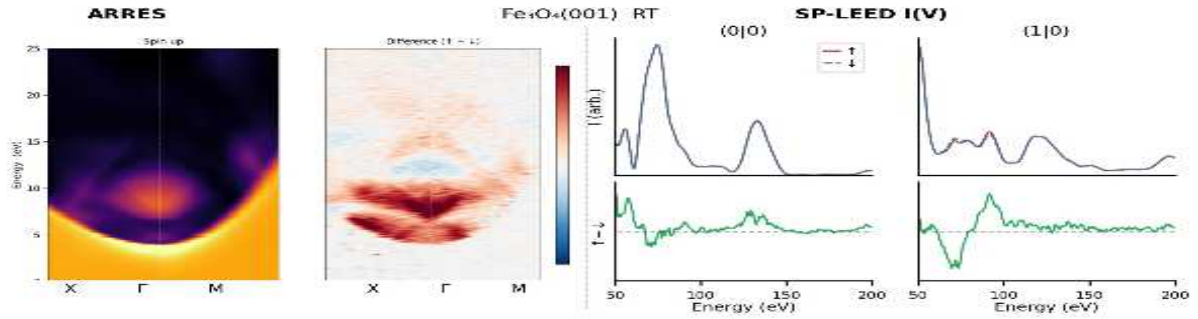


Fig. 1. Left: spin-up and difference (↑−↓) ARRES maps along X–Γ–M. Right: SP-LEED I(V) for the (0|0) and (1|0) beams at RT, spin-up (red), spin-down (blue dashed), and difference (green).

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Tu-PM-09

Using Momentum Microscopy as a Screening Tool for Many-Body Interactions in Electronic Band Structures

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State-of-the-art momentum-resolved photoemission electron microscopes (*k*-PEEMs) can access large regions of the momentum space from µm-scale surface areas, at fixed light-to-sample geometries and with sub-20-meV and sub-0.01 Å^{-1} resolutions [1]. Despite this, using *k*-PEEM to resolve fine structure in electronic band dispersions, such as many-body interaction signatures, has remained largely underappreciated.

We argue that *k*-PEEM constitutes an efficient and accessible screening tool for many-body-derived energy renormalizations, capable of guiding targeted, higher-resolution synchrotron ARPES studies. Previously, *k*-PEEM surveys have uncovered both charge transfer and interlayer confinement effects [2,3]. Herein, we will explicitly demonstrate how its use can be extended to the many-body physics regime, exemplifying our workflow through two laboratory-source studies [4,5]: electron-phonon coupling signatures in the π-band of exfoliated hexagonal boron nitride (hBN); and phonon- and magnon-coupling to the spin-split surface resonance electrons of Ni(111). In both cases, *k*-PEEM is used to identify the relevant renormalization signatures, and then subsequently confirmed and quantified using µm-scale, synchrotron ARPES (see Fig. 1). Given the growing availability of laboratory-based momentum microscopes, our two-step approach offers an accessible and high-throughput route to uncover overlooked many-body physics in systems where spatial selectivity is essential.

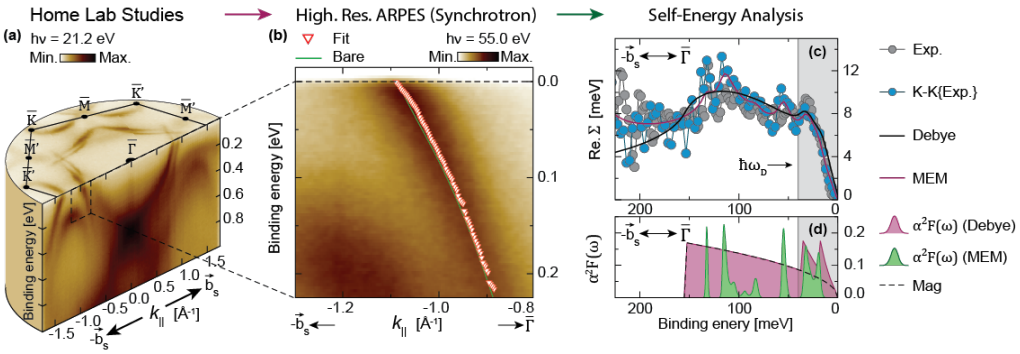


Fig 1. Many-body physics discovery from Ni(111). (**a**) *k*-PEEM screening → (**b**) synchrotron ARPES → (**c**) self-energy quantification and disentanglement of electron-boson couplings.

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Tu-PM-10

Chirality and Unconventional Charge Ordering in Kagome Metal CsV_3Sb_5

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We present an update on our ongoing research into the spontaneous emergence of electronic and crystal chirality in the Kagome metal CsV_3Sb_5 when it transitions to the charge-density wave (CDW) phase. Using angle-resolved photoemission spectroscopy and X-ray photoelectron diffraction (XPD) with circularly polarized photons, we study changes in photoemission intensity driven by dynamics in the geometric and electronic structure. We found that the system exhibits non-trivial magnetic circular dichroism in the angular distribution of photoelectrons (MCDAD), indicating magnetic ordering in the CDW phase [1]. This observation is consistent with the proposed unconventional orbital loop current order. However, as systems also exhibit local chirality in the crystal structure, the formation of the orbital loops remains elusive. We hypothesis that this originates from lattice distortion in the CDW phase and van Hove singularities (vHSs) that are close in energy and have an opposite sign.

To answer this question, we doped the system with two elements: isoelectronic but larger Nb atoms and isochor Cr atoms that have an additional electron. We found that the MCDAD signal became even more pronounced with isoelectronic Nb doping [2]. Furthermore, we performed pump-probe experiments to study the dynamics of the electron band structure. Our results reveal that the spectral intensity exhibits slow dynamics in the hundreds of femtosecond range, which is evidence of strong electron-phonon interactions in the CDW phase.

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Tu-PM-11

Surface Fermi Arcs in a Chiral Magnet

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Magnetic chiral crystals exhibit unusual transport properties, such as the skyrmion-induced topological Hall effect, creating new opportunities for next-generation electronic devices. However, linking these macroscopic responses to their electronic structure remains a major challenge, as chirality, magnetism, and topology are strongly intertwined. Our recent study demonstrates that, in the non-magnetic chiral crystal CoSi, the orbital angular momentum (OAM) serves as the main driver for the non-trivial band topology [1]. In contrast, MnSi hosts a complex magnetic order, making it an ideal platform to explore the interplay among magnetism, OAM and non-trivial topology. Chiral materials are of particular interest because they embody the ultimate form of broken symmetry. Momentum microscopy is well suited for studying these materials. Its ability to simultaneously image multiple surface Brillouin zones enables comprehensive mapping of chiral electronic structures with varying light polarizations and spin resolution [1,2]. Here, we study a clean MnSi(100) surface prepared by Ar-ion sputtering and electron-beam annealing. Through momentum microscopy, we optimized the surface preparation procedure based on a series of PEEM images and recorded electronic states of MnSi(100) over a range of binding energies in the momentum mode. By using different photon energies, which select different k_z values, we predominantly examine both bulk and surface states. Notably, the helicoid Fermi arc was observed and rotates continuously with increasing binding energy. Beyond the specific case of MnSi, our results highlight the potential of momentum microscopy for resolving complex electronic structures in magnetic chiral materials.

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We-AM-01

«All-in-one» Setup for Photoelectron Microscopy

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We present a study of various operation modes of the multimode objective lens [1]. Ray-tracing calculations and experimental examples of the following modes will be shown:

- **ARPES** (k-PEEM), illustrated for a Kagome material [2]
- Photoelectron diffraction **PED** with large angular range, examples in Ref. [3]
- PEEM and k-imaging through small pinhole for **near-ambient-pressure (NAP)** applications (first PEEM results will be shown)
- Large-field **XPEEM** (>7mm) for a new approach to RIXS, termed **PAXRIXS** [4].

The key feature of this lens is the capability of shaping the field in the gap between the sample and the first electrode. This is enabled by a ring-shaped electrode concentric to the extractor, see Fig. 1(a). Applying positive or negative voltages to the electrodes enables accelerating, zero-field or retarding-field operation. Fig. 1(b) shows an extreme case of the so-called *repeller mode* with a retarding field of F= -350 V/mm at the sample surface and a saddle point of S = -755V (with respect to the sample potential). This field acts as a strong lens with the first k-image being located already at 3.5 mm and the first Gauss image at 6 mm behind the sample, see scale bar in Fig. 1(b). We can place a small aperture in the Gauss image; here we simulated for 100 and 150 µm. This aperture can act as vacuum barrier for measurements at elevated pressure. The repeller field eliminates the main contribution to the space charge interaction.
Another limiting case is the PAXRIXS application [5] where a large FoV is imaged in XPEEM mode. These extreme cases (100µm aperture and up to 7 mm FoV) illustrate the broad parameter range enabled by the multimode front lens.

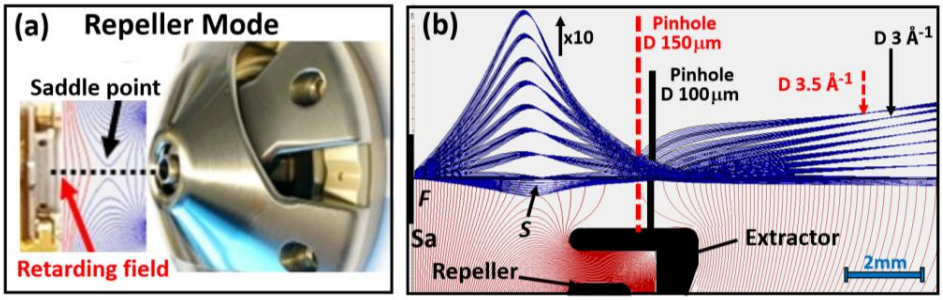


Fig 1 (a). Repeller mode of the multimode lens with a retarding field at the sample surface (red equipotential contours). The photo shows the lens geometry with a ring electrode concentric to the extractor. **(b)** Ray tracing for k-imaging through small pinholes (here 150 and 100 µm) for NAP applications. Parameters for the soft X-ray range: E_{kin}= 800 eV and a photon footprint of 40 µm.

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We-AM-02

Development of a Picosecond Spin-Polarized Electron Beam for Pump-Probe Spectroscopy in the QSPLEEM

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The Quantum Spin-Polarized Low Energy Electron Microscope (QSPLEEM) probes magnetic order, spin textures, and spin-dependent surface scattering at cryogenic temperatures. Stroboscopic pump-probe approaches have extended electron microscopies into the ultrafast regime, using pulsed photoemission in time-resolved PEEM [1] and laser-triggered electron probes in ultrafast electron microscopy [2]. In this work, we adapt the latter strategy to SPLEEM. In conventional SPLEEM, circularly polarized near-bandgap light illuminates a p-doped GaAs photocathode, producing spin-polarized photoelectrons. Cesium/oxygen activation creates a negative-electron-affinity surface that emits these electrons into the microscope column.

Here, we replace the continuous-wave excitation with a fs laser to generate ps spin-polarized electron packets. An optical pump excites the sample while a delayed electron pulse probes changes in the transient reflectivity or spin-dependent scattering. We characterize electron yield, energy spread, temporal response, image formation, and the spin polarization of the pulsed beam. Fig. 1A compares images of atomic steps on a W(110) surface acquired using different beam currents, demonstrating space-charge-induced resolution degradation. As a benchmark, we measure surface photovoltage relaxation in p-type GaAs(100), where optical excitation changes near-surface band bending and produces a delay-dependent shift in the measured work function (Fig. 1B). These nonmagnetic measurements establish operating conditions of the pulsed cathode and prepare the instrument for our future studies of ultrafast spin scattering phenomena.

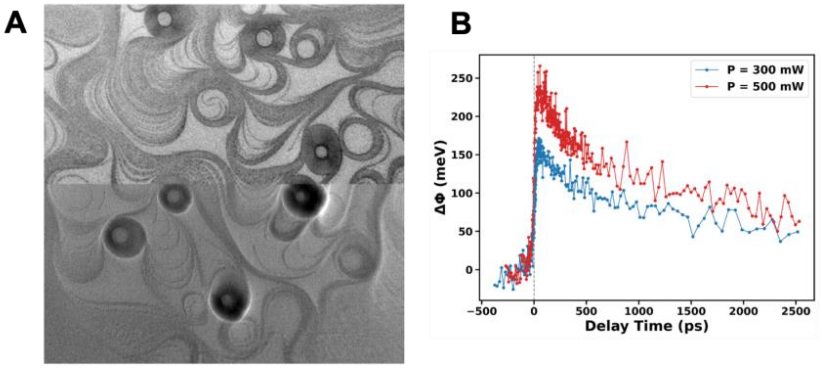


Fig 1. A) Images of atomic steps on W(110), the top and bottom panels were acquired using ~0.01 and ~0.25 μA respectively. WC contaminants have nucleated along step edges. **B)** SPV relaxation in p-GaAs(100).

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We-AM-03

Imaging Spin Filter for NanoESCA: from proven scattering targets towards full vectorial spin detection

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Energy-filtered photoelectron microscopes such as the NanoESCA [1] combine real-space imaging, imaging XPS and momentum microscopy (ARPES) on locally defined sample regions. Adding spin sensitivity allows for direct access of the spin-polarized electronic structure of magnetic materials, topological insulators, 2D systems and other spin polarized materials. The key is a two-dimensional imaging spin filter, which processes the full image simultaneously by scattering at a single-crystal target, raising the effective figure-of-merit by nearly four orders of magnitude compared to single-channel detectors [2]. Here we present the Imaging Spin Filter for the NanoESCA and its development towards full vectorial spin detection. It can be operated with several scattering targets. The Au/Ir(001) target is a proven technology. Using spin–orbit scattering, it provides a single spin component perpendicular to the scattering plane, with a well-characterized Sherman function at two working points of opposite spin contrast [2]. Stable over several weeks in UHV, it enables true quantitative spin-polarization analysis; first instruments have already been commissioned in the field. Alternatively, an oxygen-passivated iron film, Fe(001)-p(1×1)O, serves as an exchange-scattering target, where integrated coils select the spin-sensitive direction by magnetizing the film. In a proof-of-principle measurement on polycrystalline iron, two perpendicular spin components were imaged in a single fixed setup without any change of geometry or electron optics (Fig. 1) [2].

Finally, we introduce a new Imaging Spin Rotator, currently at prototype stage with initial functionality already successfully demonstrated. Mutually rotating all spin components by 90 degrees, while keeping the microscope image intact, paves the way towards full vectorial imaging spin detection.

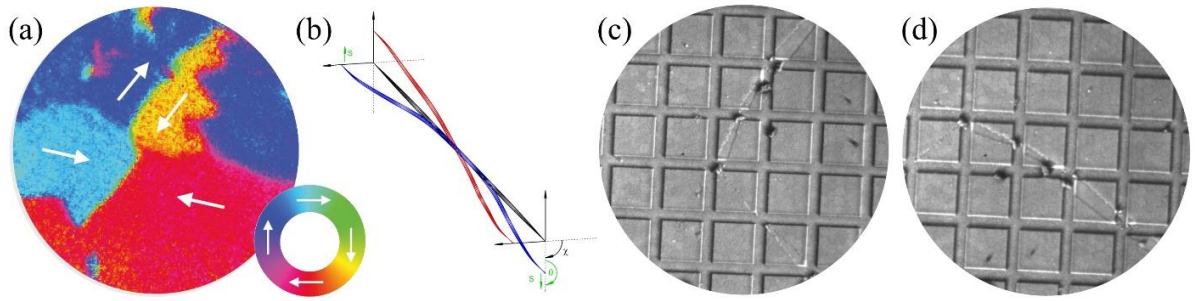


Fig 1. Magnetic domains of polycrystalline iron, measured with two perpendicular spin components (a). Electron trajectories of the spin rotator (b). A 90 degree rotation was performed on a test sample (c,d), the spin would rotate twice this angle [3].

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We-AM-04

Exchange-coupled domains in $NiO/Fe_3O_4(001)$ across the Verwey transition visualized by XMCD- and XMLD-PEEM

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In this work, we investigate the temperature-driven evolution of interfacial exchange coupling between epitaxial antiferromagnetic NiO films and ferrimagnetic $Fe_3O_4(001)$ across the Verwey transition. Previous studies showed predominantly collinear domain coupling in $NiO/Fe_3O_4(001)$, with the NiO spin axis aligned in-plane along the Fe_3O_4 <100> directions [1,2].

The Verwey transition provides an internal perturbation to this coupled system, as Fe_3O_4 undergoes a lowering of crystal symmetry [3], accompanied by changes in magnetic anisotropy and domain configuration [4]. Using complementary XMCD- and XMLD-PEEM at room temperature and below the Verwey transition, we directly compare the ferrimagnetic Fe_3O_4 and antiferromagnetic NiO domain configurations. To our knowledge, this is the first PEEM observation showing that the NiO XMLD contrast follows the Verwey-transition-induced reorganization of the Fe_3O_4 magnetic domain pattern, demonstrating robust interfacial exchange coupling.

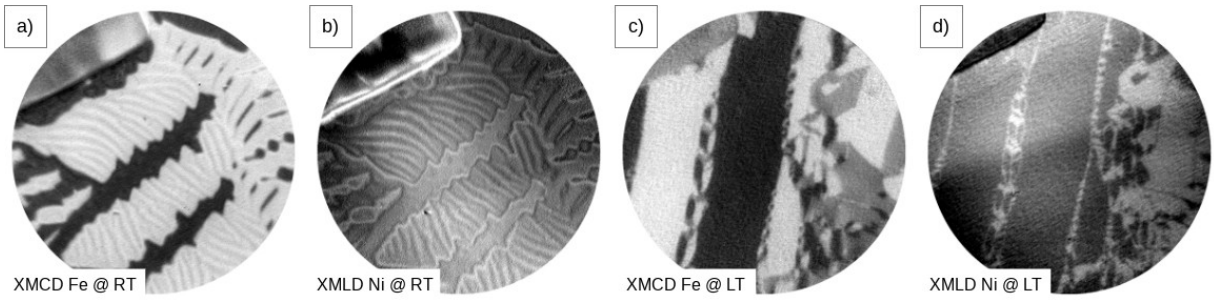


Fig 1. XMCD-PEEM and XMLD-PEEM images acquired at the Fe L_3 and Ni L_2 absorption edges, respectively, showing the ferrimagnetic Fe_3O_4 magnetic domain structure and the corresponding antiferromagnetic NiO domain contrast in $NiO/Fe_3O_4(001)$ at room temperature (a,b) and below the Verwey transition (c,d).

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We-AM-05

Direct Observation of Chiral Magnon Splitting in Altermagnetic CrSb

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Altermagnetism is a recently identified class of magnetic order combining the spin-polarized electronic bands characteristic of ferromagnets and the zero net magnetization of antiferromagnets. It arises from crystal rotational symmetry rather than spin-orbit coupling. Although the static electronic properties of altermagnets in their ground state have been well-characterized, their dynamic spin excitations, or magnons, are not well understood. Theory predictions suggest that altermagnetic order lifts the degeneracy of chiral magnon branches along specific directions in reciprocal space, resulting in magnons of opposite chirality with different energies. This splitting is closely linked to the underlying spin-split electronic structure and is expected to enable non-reciprocal magnon transport. This property is of considerable interest for spintronic and magnonic devices operating at terahertz frequencies. Despite this theoretical motivation, direct experimental confirmation of chirality-resolved magnon energy splitting has remained elusive. Here, we present direct evidence of energy-split chiral magnons in the hexagonal altermagnet CrSb using a single instrument that combines angle-resolved photoemission spectroscopy (ARPES) and resonant inelastic X-ray scattering (RIXS) via the photoelectron-detection (PAX) method. We selectively excite electronic and magnonic states with opposite spins and quantify their energy splitting. We find that the non-degeneracy of electronic and magnonic states exists away from high-symmetry directions, which is in good agreement with recent *ab initio* calculations. Our experimental proof of chiral magnons demonstrates a new degree of freedom in magnetism that is both of fundamental importance and opens the door to exploring the non-reciprocal transport properties of these bosons in devices [1].

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We-AM-06

From Interfacial Chirality to Complex Spin Textures with Spin-Polarized Low-Energy Electron Microscopy

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Spin-polarized low-energy electron microscopy (SPLEEM) uniquely provides real-space, vector-resolved imaging of surface magnetization. Over the past decade, our SPLEEM studies have expanded from quantitative characterization of interfacial magnetic chirality to engineering topological spin textures and, more recently, exploring antiferromagnetic spin configurations in van der Waals and oxide materials.

These studies provide quantitative insight into chiral magnetic interactions and their microscopic origins, while demonstrating versatile routes for engineering magnetic chirality through interfacial modification, symmetry control, and related strategies. This enables deterministic manipulation of topological spin textures with tunable topology, while ongoing efforts are focused on developing new SPLEEM imaging capabilities for increasingly complex magnetic systems.

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We-AM-07

$Nd_2SrFe_2O_7$: a layered antiferromagnetic perovskite with a twist

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The layered double perovskite Nd2SrFe2O7 (NSFO) [1] is a room-temperature antiferromagnet (AF) that has attracted renewed interest following the discovery of rich structural textures [2], including Z_8 vortex-antivortex pairs [3]. The density of these topological defects can be tuned by the cooling rate through the structural transition, following the universal behaviour expected from the Kibble-Zurek mechanism.

Despite this interest, the antiferromagnetic structure of NSFO has remained ambiguous. X-ray and neutron diffraction (ND) alone cannot unambiguously distinguish between the collinear Pnmn.1 and layered $P4_2/mnm.1$ magnetic structures [4].

By combining ND with X-ray magnetic linear dichroism photoemission electron microscopy (XMLD-PEEM), we show that NSFO exhibits collinear antiferromagnetic order within the *ab* planes, with the Néel axis alternating between the [110] and [−110] directions in adjacent perovskite layers. This configuration is compatible only with the $P4_2/mnm.1$ magnetic space group. Moreover, we find that the AF domain walls retain a common Néel-axis orientation across successive perovskite layers, in contrast to the alternating orientation observed in the AF domains. XMLD-PEEM further reveals antiferromagnetic vortex–antivortex pairs and a maze-like network of antiphase domain-wall boundaries with two distinct spin orientations. These magnetic textures are directly associated with the oxygen-octahedral tilting previously identified by X-ray diffraction [4] and transmission electron microscopy [3].

We will also discuss the effect of applying high magnetic fields of up to 12 T at room temperature, which generate stripe-like domains reminiscent of those observed in the high-temperature orthorhombic O′ paraelectric phase [3].

Finally, the magnetic symmetry of NSFO, together with the presence of staggered antiferromagnetic planes whose Néel axes are mutually orthogonal, suggests a possible altermagnetic character. These results establish NSFO as a model system for studying the interplay between structural topology, antiferromagnetic order and emergent altermagnetic functionality, while highlighting its potential relevance for future spintronic applications.

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We-AM-08

Engineering magnetism in two-dimensional magnets

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Two-dimensional (2D) magnetic materials have emerged as a frontier in condensed matter physics and materials science because they provide an ideal platform for exploring fundamental magnetic phenomena at the atomic limit. The discovery of intrinsic long-range magnetic order in atomically thin crystals has challenged conventional understanding of low-dimensional magnetism and opened new opportunities for investigating spin interactions, magnetic anisotropy, topological spin textures, and magnetic phase transitions. Owing to their strong coupling between spin, charge, lattice, and orbital degrees of freedom, the magnetic properties of 2D materials can be efficiently tuned by external stimuli such as electric fields, strain, light, and chemical engineering. This exceptional tunability not only enables the discovery of novel quantum states but also provides a versatile platform for designing next-generation functional magnetic materials. Herein, we modulate the interlayer magnetic interaction by cobalt doping in Fe5-xGeTe2[1, 2]; The interlayer magnetic interaction was observed in the CrSBr/Fe3GaTe2 heterostructure [3]; The chiral magnetic domains was realized through self-intercalation in CrTe2 [4]; The magnetism can be tuned by strain in CuCr2Se4 [5].

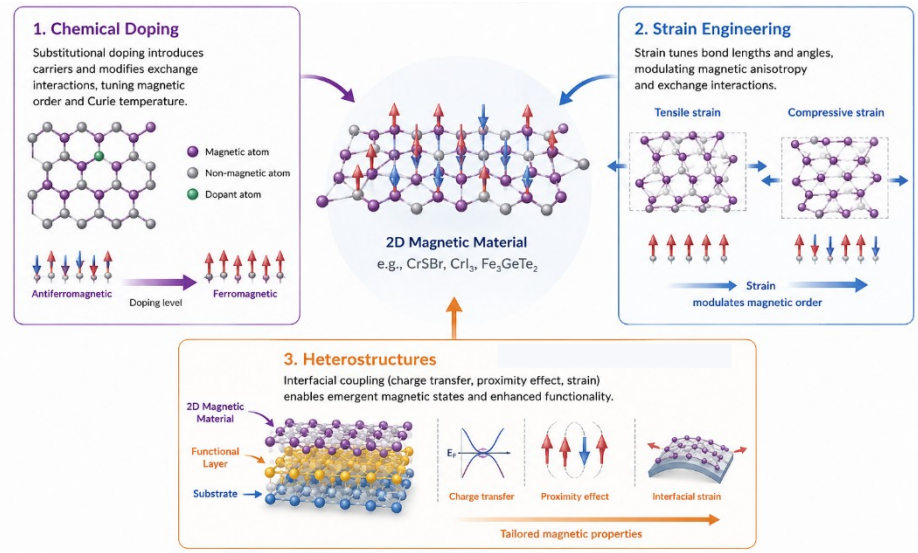


Figure 1. Magnetism engineering in 2D magnetic materials by doping, strain and heterostructure.

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We-AM-09

Emergent Magnetic Textures in Permalloy/Hematite Bilayers

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Heterostructures combining antiferromagnetic (AFM) and ferromagnetic (FM) phases provide a versatile platform with rich functional phenomena for spintronic applications. Hematite is particularly attractive due to its Morin transition, where the AFM moments reorient from a basal plane to a c-axis configuration when lowering the temperature. In permalloy/hematite bilayers, FM/AFM coupling has been shown to induce enhanced coercivity and exchange bias across the Morin transition [1,2]. Here, we investigate permalloy/hematite bilayers using XMCD-PEEM and MOKE imaging of the FM domains. We observe novel isolated closed magnetic textures, where the reconstructed vector maps reveal a 360° rotation of the magnetization across the ring wall. The underlying AFM Néel vector plays a decisive role, since the stabilization of the ring texture is influenced by a complex interplay between interfacial exchange with the underlying AFM spin structure and magnetic anisotropy, among other terms. Our results reveal a strong influence of the hematite Néel order on the FM magnetic texture and on the orientation and morphology of non-trivial emergent magnetic textures.

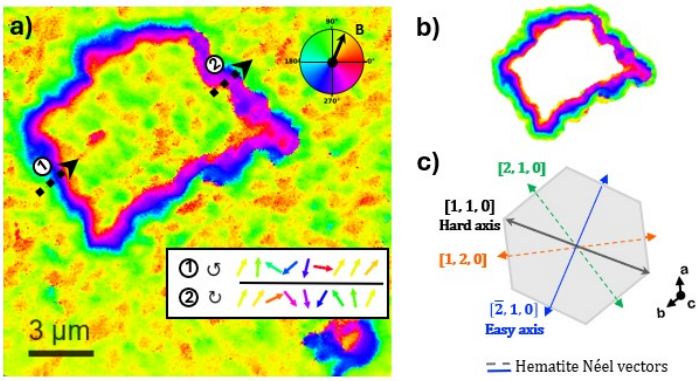


Fig 1. a) Vector map XMCD-PEEM image showing in-plane magnetization and representative rotation sequences across a ring texture. b) Extracted ring from the vector map c) Hematite basal plane showing the Néel vector directions (blue, red and green) and permalloy easy and hard axes.

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We-PM-01

Latent image and intrinsic inhomogeneity in resists visualized by laser-based photoemission electron microscopy

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The increasing demand for further advancement of state-of-the-art EUV lithography has heightened the importance of high-throughput inspection techniques [1]. Direct observation of chemical patterns formed by exposure process (latent images) in electron-beam- (EB) and photo-resists prior to development process would enable rapid optimization of exposure and development conditions. Although infrared atomic force microscopy (IR-AFM) can be used to observe latent images [2], its low throughput limits its applicability in high-volume manufacturing.

We have demonstrated that photoemission microscopy using a continuous-wave (CW) laser light source can achieve a world-leading spatial resolution of 2.6 nm with an exposure time of 0.1 s [3]. In this study, we demonstrate that laser-based photoemission electron microscopy (laser-PEEM) enables high-throughput observation of latent images in EB resists [4]. Line-and-space (L/S) patterns were fabricated in an EB resist, and samples before and after development were comparatively evaluated using laser-PEEM, AFM, and scanning electron microscopy (SEM).

Laser-PEEM imaging revealed that EB-exposed regions appear as dark contrast. For developed patterns, laser-PEEM is suggested to achieve comparable spatial resolution and signal-to-noise ratio (S/N) to SEM, while achieving over 10,000 times higher throughput than a single-beam SEM.

In addition, laser-PEEM was shown to be capable of detecting intrinsic chemical inhomogeneities in the resist, demonstrating its utility as a chemical-state imaging technique beyond mere morphological observation. Furthermore, we succeeded in visualizing latent images in a conventional photoresist [5]. This work highlights the potential of laser-PEEM as a transformative high-throughput inspection technique for next-generation semiconductor manufacturing, and opens new opportunities for research in latent image imaging of resists.

Acknowledgement: This work was supported by Hitachi High-Tech Corporation. We also acknowledge support from Oxide Corporation for the implementation of the CW laser. We thank Y. Mizuno for her technical support with the laser-PEEM measurements, and M. Oshima and T. Arima for their valuable discussions. We also acknowledge Y. Hashimoto and A. Endo for their technical support in fabricating the latent-image samples using the EB lithography in the Q-NanoLab in ISSP. This work was supported by Precise Measurement Technology Promotion Foundation and by Murata Science and Education Foundation.

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We-PM-02

Defect Inspection in Wide Band Gap Power Devices

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Silicon carbide (SiC) power MOSFETs are increasingly preferred for advanced power electronics due to their low switching losses, high breakdown voltages, and fast switching speeds. Their reliability is limited by degradation mechanisms, especially body-diode degradation linked to crystallographic defects in the SiC material [1]. Basal plane dislocations (BPDs) can transform into Shockley stacking faults (SSFs), increasing carrier recombination, causing forward voltage drift [2], and reducing device performance and lifetime.

Recently, laser-based photoemission electron microscopy (laser-PEEM) has been reported to probe and identify the defects in GaN [3] and β-Ga_2O_3 [4]. In the present study, we used laser-PEEM to investigate extended defects in SiC planar MOSFETs. One device (device #2) displayed anomalously elevated onset of conduction current [5] at low voltage compared with other devices. PEEM imaging revealed numerous elongated bar-shaped and needle-like defects aligned along the <11$\bar{2}$0> crystallographic direction. These features became more distinct at increased UV wavelengths and showed electronic states shifted toward lower energies, indicating defect-related behavior. In contrast, another device (device #23) displayed normal electrical characteristics and only a single triangular feature with no distinct electronic signature. The observed features in device #23 are hypothesized to be crystallographic in nature.

This work demonstrates that laser-PEEM is a powerful, nondestructive technique for detecting and characterizing extended defects in SiC MOSFETs that may be difficult to identify using conventional methods. Further, we aim to develop *operando* capability with the existing PEEM to evaluate the surface features in response to current injection to the devices.

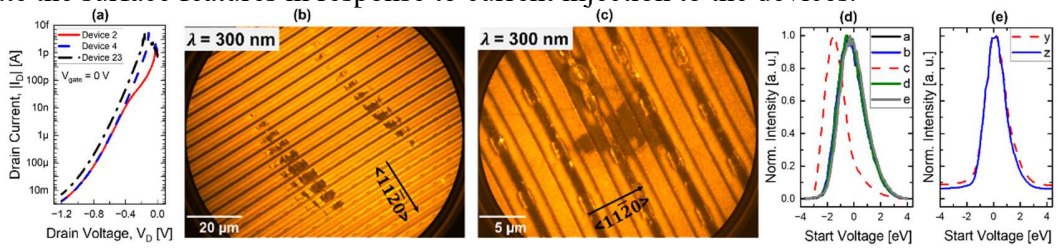


Fig 1. (a) Low I-V electrical measurements, laser-PEEM images of (b) device #2 at λ = 300 nm and (c) device #23 at λ = 290 nm, voltage scans at 200 nm on and off the features for (d) device #2 and (e) device #23.

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We-PM-03

Tracing charge carriers in organic molecular crystals using PEEM

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Organic molecular crystals exhibit interesting optoelectronic properties, yet their performance is determined by local structural disorders or interfaces that are difficult to study with conventional techniques. In this work, we use photoemission electron microscopy (PEEM) to image the electronic landscape of organic molecular crystals and reveal the microscopic processes that drive charge-carrier behaviour. Using wavelength dependent time-of-flight spectromicroscopy, we investigate charge generation [1,2], transport [3], trapping [1,3], and accumulation [2,3] in rubrene-based organic molecular crystals. The measurements reveal how crystal morphology, molecular orientation and nanoscale interfaces influence local conductivity and photoemission response. A key result is transient charging due to dynamic gating by roaming charge carriers.

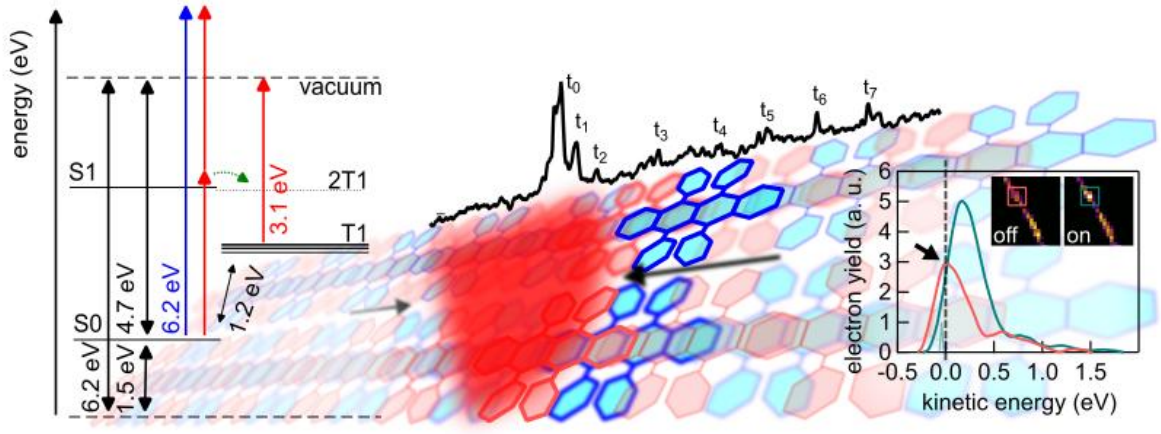


Fig 1. Scheme of photoemission intermittency at the organic-nanoparticle interface (red spot) driven by stochastic gating with exemplarily electron yield time trace. (Right) electron spectra of the intermittent site at On and Off photoemission events, respectively. (Left) Energy diagram of a 2D rubrene crystal, where singlet fission is indicated by a green arrow.

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We-PM-04

LEEM/PEEM as versatile probe of functional materials for microelectronics

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Low-energy electron microscopy (LEEM) and photoemission electron microscopy (PEEM) are established as spectromicroscopic techniques capable of delivering spatially resolved structural, chemical, electronic, and magnetic information across a wide range of material systems relevant for microelectronics.

In next-generation memory technologies, PEEM-based photoemission threshold mapping and operando X-ray absorption spectroscopy were applied to resistive switching memristive devices to image conductive filament formation in $SrTiO_3$ [1]. The technique directly visualized cycle-to-cycle variability arising from the coexistence of multiple sub-filaments whose active configuration changes stochastically between switching events. In two-dimensional materials, spatially resolved PEEM with sub-30-nm resolution was used to map core-level binding energy shifts across WSe_2/MoS_2 van der Waals hetero-bilayers, quantifying the interfacial contact potential and charge transfer between the two constituent monolayers [2]. These measurements measured a band alignment of the device and a built-in potential of up to 400 meV arising from the work function difference—information not accessible by conventional area-averaging spectroscopies and directly relevant for engineering optoelectronic vdW devices. Finally, soft X-ray PEEM with X-ray linear dichroism (XLD) contrast was applied to individual flakes of the 2D transition metal carbide $Cr_2TiC_2T_x$ MXene [3], providing spatially localized chemical and electronic spectra that confirmed the intrinsic nature of a low-temperature magnetic spin-freezing transition at ~30 K. PEEM's chemical imaging capability simultaneously ruled out the presence of chromium oxide nanoparticles as a spurious origin of the magnetic signal—a critical control that spatially-averaging bulk techniques cannot provide.

Together, these examples illustrate that LEEM/PEEM proves to be a versatile surface-science toolkit for microelectonics: a single instrument platform delivering real-space imaging with tunable structural, chemical, and magnetic contrast.

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We-PM-05

Spatiotemporal Imaging of Current-induced Domain Wall Depinning

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Magnetic domain walls are promising functional elements in spintronic devices due to their nanoscale scalability and ultrafast nonlinear responses to electrical stimuli in the MHz-to-GHz regime [1]. These behaviors originate from inherently non-equilibrium dynamics governed by the interplay between spin-transfer torque and pinning potential [2], making it challenging to identify the fundamental timescale that limits device response.

Ultrafast transmission electron microscopy, which combines the pump-probe method and transmission electron microscopy (TEM), has emerged as a versatile platform for visualizing non-equilibrium phenomena in nanostructures [3]. Recent advances in operando magnetic imaging using Lorentz TEM have further enabled the visualization of current-induced dynamics in magnetic systems with nanometer-nanosecond resolution [4, 5].

In this work, we employ time-resolved Lorentz TEM to investigate the current-induced depinning of a ferromagnetic domain wall. We uncover a characteristic incubation time preceding depinning, which becomes strongly enhanced near the depinning threshold. Micromagnetic simulations reveal that the incubation time arises from a dynamical bottleneck caused by the near cancellation of the net driving force. Our results identify a previously inaccessible dynamical limit governing the onset of domain wall motion and provide a framework for understanding response bottlenecks in nanoscale spin textures.

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We-PM-06

Real-Space Imaging of Orbital Nematicity across the phase diagram of $Ba_{1-x}Na_xFe_2As_2$

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Electronic nematicity has attracted considerable attention as a characteristic electronic state in iron-based superconductors. It is characterized by the spontaneous breaking of the in-plane rotational symmetry of the electronic system while preserving translational symmetry. In real space, such electronic symmetry breaking can lead to mesoscopic nematic domains.

In this work, we focus on $Ba_{1-x}Na_xFe_2As_2$, a representative hole-doped 122-type iron-based superconductor. Upon Na substitution, the competition between its antiferromagnetic ground state and a superconducting ground state gives rise to multiple intermediate states with peculiar symmetries, as mapped by figure 1. Such rich phase diagram offers an opportunity to examine whether the spatial characteristics of nematic domains reflect the underlying electronic phase environment.

Using our cryogenic laser-excited photoemission electron microscope, we investigate the nematic-domain features across the phase diagram of $Ba_{1-x}Na_xFe_2As_2$. Thanks to a sizable linear-dichroic contrast, due to the orbital anisotripy charateristic of the nematic state, we can visualize the nematic domains size and the domain walls length, as illustrated by the figure 2. We explore the evolution of this nematic-domain morphology across different regions of the phase diagram. Detailed experimental results and discussion will be presented with reference to our presentation.

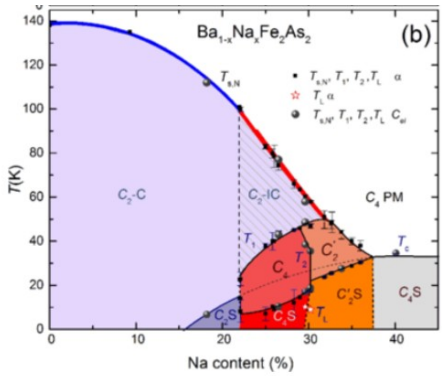


Fig 1 Phase of $Ba_{1-x}Na_xFe_2As_2$[1]

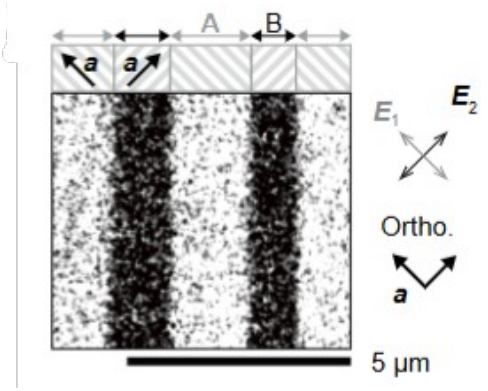


Fig 2 Real space image of nematic domains[2]

References:

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We-PM-07

Structural and Chemical Evolution of an N-Enriched Fe(111) Surface during Near-Ambient-Pressure Ammonia Synthesis

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Ammonia synthesis over iron catalysts is highly structure sensitive [1], and the catalyst surface can undergo significant structural and chemical evolution under reaction conditions [2,3]. Understanding the relationship between surface dynamics and local chemical environments under near-practical reaction conditions is important for elucidating the behavior of iron catalysts during ammonia synthesis [4,5]. In this work, we investigate the structural and chemical evolution of an N-enriched Fe(111) single crystal surface during quasi *in-situ* ammonia synthesis by combining Low-Energy Electron Microscopy/Diffraction (LEEM/LEED), X-ray Photoemission Electron Microscopy (XPEEM), and X-ray Photoelectron Spectroscopy (XPS). Our results show that nitrogen enrichment induces the reversible formation of highly ordered (212) facets on the Fe(111) surface, with nitrogen species preferentially localized at the faceted regions (Fig. 1). After ammonia synthesis reaction, traces of oxygen-containing impurities preferentially accumulate at the faceted regions (Fig. 2), accompanied by a restructuring of the surface from (212)- to (211)-type facets. In contrast, suppressing oxygen impurities stabilizes the (212) facets under reaction conditions. Depth-dependent XPS measurements reveal that the distribution of NH_x intermediates strongly depends on the local chemical environment. When oxygen-containing impurities are present, NH_x species are preferentially located below the outermost surface layer (Fig. 3), whereas they are mainly observed on the topmost surface under highly purified conditions. These results demonstrate the strong coupling between local chemical environments and surface dynamics on Fe(111) during ammonia synthesis.

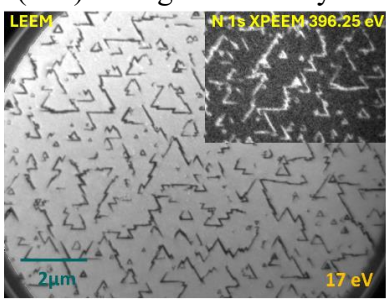


Fig 1. LEEM and N 1s XPEEM of the as-prepared N-enriched Fe (111) single crystal.

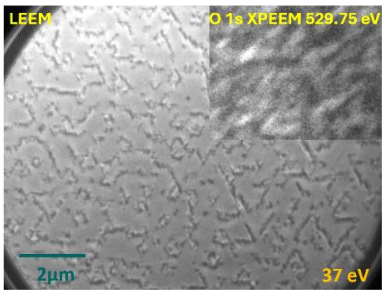


Fig 2 LEEM and O 1s XPEEM of N-enriched Fe (111) after ammonia synthesis reaction.

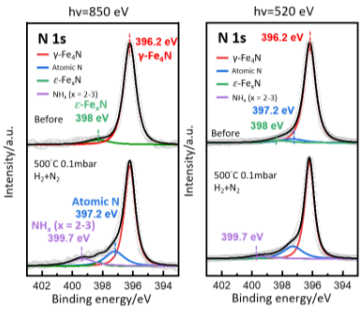


Fig 3. The N 1s XPS for the N-enriched Fe (111) before and after reaction.

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Th-AM-01

Virtual-Electrode LEEM for in-situ studies of Li and Na anode formation

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Reversible anode-free solid-state batteries require precise control of alkali-metal nucleation, growth, and dissolution at buried solid-electrolyte/current-collector interfaces, yet these processes remain challenging to probe operando. Here, we introduce virtual-electrode low-energy electron microscopy (VE-LEEM), complemented by PEEM and AFM, for direct nanoscale visualization of anode formation and dissolution. The alkali metal anode is grown (plating) directly onto the solid-state electrolyte driven by the electric charge provided by the LEEM gun (virtual electrode). The process can be reversed (stripping) by the positive charge from the photoemission process under the UV lamp illumination.

We track the early stages of Li and Na plating, showing that both systems converge towards common scaling behavior despite distinct coarsening pathways governed by surface energetics. Stripping proceeds asymmetrically through grain-boundary unzipping and cluster decay. These observations identify interfacial and cohesive energetics as key factors limiting reversibility in anode-free architectures. These results establish VE-LEEM as a powerful approach for resolving buried interfaces and guiding the design of durable, high-energy solid-state batteries [1].

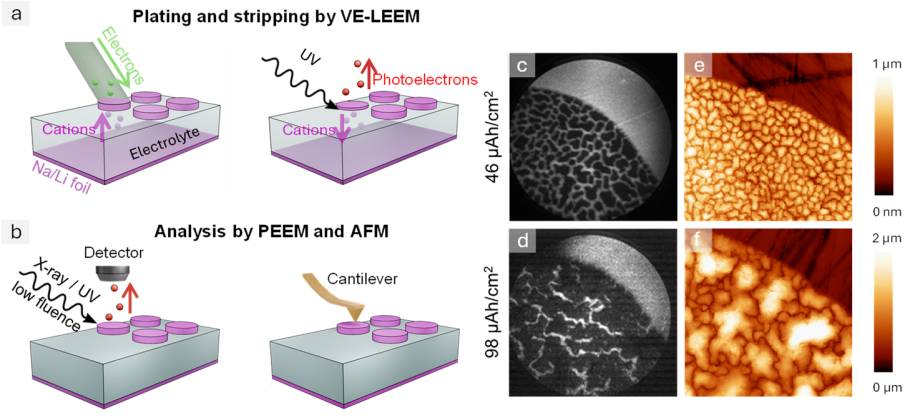


Fig 1. Schematic of the VE-LEEM approach to study the anode growth at the nanoscale (a,b), XAS-PEEM images (c,d) and AFM topographies (e,f) revealing 3D cluster formation.

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Th-AM-02

Measuring spherical and chromatic aberrations in Elmitec AC-SPELEEM

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Aberration correction has been a major advance in PEEM and LEEM systems. By introducing an electrostatic tetrode mirror, both spherical and chromatic aberrations can be compensated, enabling LEEM spatial resolutions approaching 2 nm. Commercial aberration-corrected LEEM/PEEM systems are currently available from Elmitec and Specs, with pre-calculated tetrode lens settings implemented in the microscope control software. While the aberration coefficients of the Specs system have been quantitatively characterized by Tromp et al., corresponding measurements on Elmitec systems have been less extensively reported. Here, we present quantitative measurements of spherical and chromatic aberrations in an Elmitec aberration-corrected LEEM/PEEM system. By comparing corrected and uncorrected imaging conditions, we demonstrate that the correction mirror effectively compensates both types of aberrations when properly aligned and tuned. These measurements provide a practical basis for evaluating corrector performance, optimizing microscope alignment, and identifying residual optical errors that may limit spatial resolution, image quality, and operational stability.

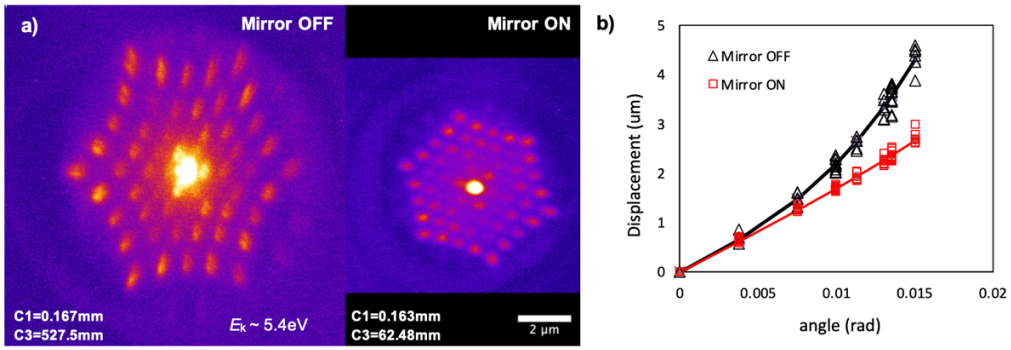


Fig 1. a) Real-space low energy electron diffraction (RSLEED) images recorded with the aberration-correction mirror switched off and on, showing a substantial reduction of spherical aberration in the corrected mode. (b) Displacements of diffraction spots from the (00) beam as a function of emission angles. The data are fitted with $\delta_s = c_1\alpha + c_3\alpha^3$, where c_1 and c_3 denote the defocus and spherical aberration coefficients, respectively. Note that the sample-objective distance is about 3 mm.

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Th-AM-03

First µLEED-IV Adsorbate Structure Analysis Solely by LEEM-based Data: Se and Te on Ru(0001)

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Identifying adsorption sites of single atoms is one of the most prominent challenges in surface structure analysis. Since the 1970s, LEED-IV has been established as a reliable tool for this purpose [1-3]. With increasing computing power and the development of analysis software, such as the versatile ViPErLEED package [4], this method is now routinely applicable. A remaining drawback, however, is the lack of spatial resolution in conventional LEED systems, which requires preparing homogeneous surfaces at the mm scale. An early approach to overcome this limitation was reported by de la Figuera in 2006 [5], in which the Ru(0001) surface structure was analyzed using µLEED-IV data collected from a single Ru terrace. Reichelt et al. showed that both conventional and µLEED data were in good agreement [6]. A first attempt at using quantitative µLEED-IV analysis of single oxide islands to distinguish between RuO2(100) surface terminations, however, remained inconclusive [7]. Here, we present the first full structure determination based solely on µLEED-IV data for an adsorbate system, namely the adsorption of Se and Te on Ru(0001), a model system for graphene intercalation and self-interaction in TMDCs. We obtain excellent Pendry R-factors of 0.12 or lower, comparable to state-of-the-art conventional LEED-IV studies.

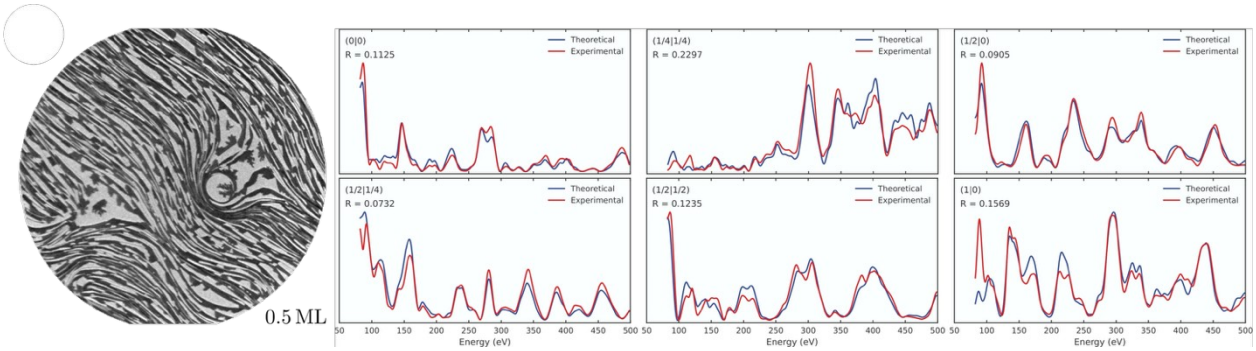


Fig 1. LEEM image and µLEED-IV analysis of $(2\times\sqrt{3})_{rec}$-Te on Ru(0001);

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Th-AM-04

Mixed or pure: F16CuPc and CoPc on Ag(100) surfaces

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Phthalocyanine (Pc) molecules on single-crystalline surfaces are often studied as model systems due to their symmetry, thermal stability, and chemical stability. On Ag(100) surfaces, replacing hydrogen with fluorene in the outer part of the Pc molecules alters the work function of ultrathin films. H-terminated Pcs lower the work function, while F-terminated Pcs increase it. We used PEEM with the mean electron yield as the indicator to monitor the growth of ultrathin films. By analyzing the standard deviation of the individual images, we confirmed that even at nominal coverages as high as 0.8 monolayer, only a two-dimensional gas phase is present on the surface.[1] DFT calculations show that surface-mediated repulsion causes the delayed condensation of crystalline structures.[2] Immediate condensation can be achieved by depositing small amounts of Pc molecules with the opposite termination (H versus F). The attractive interaction between the two Pc derivatives leads to the formation of well-defined bimolecular structures.

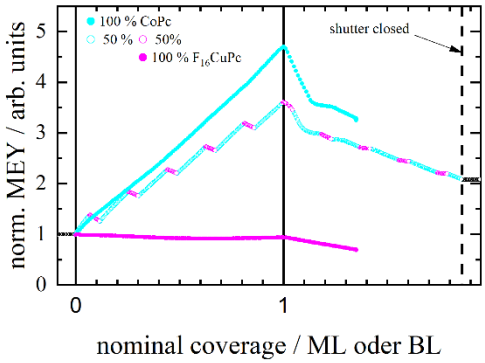


Fig 1. Evolution of the normalized mean electron yield during the deposition of either CoPc or F_{16}CuPc and alternating deposition of both on Ag(100) monitored with PEEM using a Xe lamp.

Reference(s)

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Th-AM-05

Near-edge absorption spectromicroscopy of ferroelectric $BaTiO_3$ (001)

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Ferroelectric ultrathin films feature a single domain state, stabilized by charge accumulation near surfaces [1], whose origin may be mobile charges, depletion layers or charge accumulated in adsorbates or external contacts [2]. In particular, for ultraclean films, such charge accumulation induces band bending near surface, affecting core level energies and visible in photoelectron spectroscopy. Thicker films form ferroelectric domains, whose band bending near surface was evidenced by various experiments involving spectromicroscopy [3–5], low energy electron microscopy (LEEM) or X-ray photoemission microscopy (XPEEM) [6]. This contribution investigates the ability of near-edge absorption fine structure (NEXAFS) microscopy to extract information regarding local electronic structure. Since NEXAFS relies on transitions between core and valence states, it may happen that these transitions occur at similar energies in the ferroelectric and paraelectric state, if the band bending is the same for initial and final states. We demonstrate that NEXAFS transition energies are spatially-dependent (Fig. 1). Moreover, energy shifts are atom- and state-dependent, in particular for Ti L2,3-edges transitions in the ferroelectric state occur at higher photon energies than for the paraelectric state (Fig. 2), while for O K-edge and Ba M4,5-edges the situation is reversed (Fig. 3). This is explained by different hybridizations of final state orbitals (3d t2g and eg for titanium, 3p for oxygen and 6p for barium) induced by the ferroelectricity. Other atom, state-specific and temperature dependent effects are identified and will be commented.

The measurements were carried out at the SMART instrument at the BESSY II electron storage ring of the Helmholtz-Zentrum Berlin für Materialien und Energie.

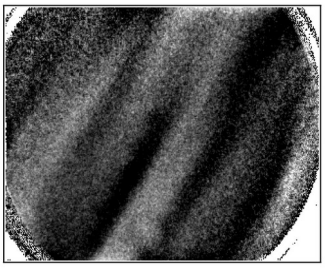


Fig. 1. Map of Ti $2p_{3/2} \rightarrow 3d\ t_{2g}$ energies. FOV = 12.2 µm.

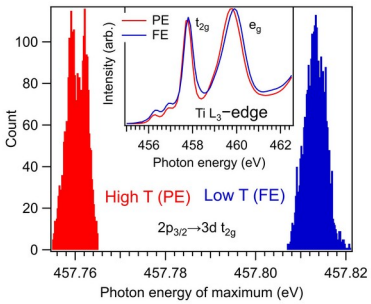


Fig. 2. Histogram of Ti $2p_{3/2} \rightarrow 3d\ t_{2g}$ transition energies.

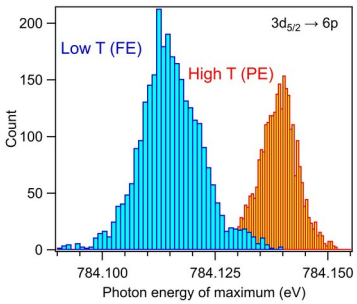


Fig. 3. Histogram of Ba $3d_{5/2} \rightarrow 6p$ transition energies.

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Th-AM-06

Templating defect arrays with moiré ferroelectricity in twisted hexagonal boron nitride

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Defects arrays with nanoscale pitches are crucial for scalable quantum technologies, but current methods lack sufficient precision. In this work, we explore instead the spatial defect distribution in small angles twisted hBN, which exhibits moiré ferroelectricity. Using Photoemission electron microscopy (PEEM) to reveal the spatial energetic landscape of hBN, we image valences, defects and even domain wall states. Surprisingly, we find that defects are preferentially localized at ferroelectric domain wall nodes for small domains, forming tunable nanoscale periodic arrays. For larger domains, defects align along the domain walls instead. Defect photoluminescence characterization shows spectral signatures consistent with known C-based single quantum emitters. This discovery provides a new pathway to spatially structure defects in van der Waals materials for quantum device development.

Acknowledgement
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Th-AM-07

Growth dynamics and chemical reactivity in Sm-doped cerium oxide inverse catalytic model systems

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Cerium oxide has been widely used in heterogeneous catalysis for several decades because of its favorable chemical properties and high oxygen-storage capacity. Fundamentally, these properties are closely linked to its flexible cubic crystal structure, which enables facile changes between the cerium cations' +4 and +3 oxidation states and the formation of oxygen vacancies, both of which have been associated with increased activity in many chemical reactions. These findings suggest a route to further enhance its activity by promoting the formation of Ce^{3+} species through alloying with transition or rare-earth (RE) metals.

Here, we present our efforts to characterize the structural and chemical transformations in Sm-doped CeO_x inverse catalytic model systems during growth and under reaction conditions, using in situ low-energy electron microscopy and micro-diffraction (LEEM/μ-LEED) and X-ray absorption spectroscopy combined with photoemission electron microscopy (XAS-PEEM). On the Ru(0001) surface, we show that nanoparticle shape, morphology, and chemistry are strongly influenced by the synthesis method, thereby modifying the reducibility of the nanoislands and increasing reactivity toward H_2 [1] and the catalytic activation of CO_2, as determined by near-ambient-pressure X-ray photoelectron spectroscopy (NAP-XPS) and atomistically explained by density functional theory (DFT) calculations. For Sm-CeO_x on the Cu(111) surface, which enables the selective growth of CeO_2(111) and CeO_2(100) nanoislands [2], we demonstrate that the interaction between the post-deposited Sm metal and the CeO_2 nanoislands is influenced by their facet orientation [3]; furthermore, we find evidence for the formation of metastable Sm-rich structures. These observations have motivated an in-depth study of the "pure dopant" Sm_2O_3 material system on both Ru(0001) [4] and Cu(111) [5] surfaces, with the latter case revealing a rather unexpected structural variety of the sesquioxide both during growth and under reaction conditions.

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Th-AM-08

Spatiotemporal imaging of charge transfer in photocatalyst particles with energy- and time-resolved photoemission electron microscopy

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Solar-driven water-splitting reactions on photocatalyst particles offer a promising route toward clean and renewable energy, with photoinduced charge separation and transfer being central to improving photocatalytic efficiency. However, elucidating the origin and holistic spatiotemporal evolution of these processes remains challenging, as they span nanometer length scales and timescales ranging from femtoseconds to seconds[1]. In this talk, I will present our work using energy- and time-resolved photoemission electron microscopy (PEEM) to map ultrafast charge transfer dynamics in single photocatalyst particles with femtosecond temporal and nanometer spatial resolution[2]. By combining this technique with spatiotemporally resolved surface photovoltage (SPV) measurements[3], we further track the complete evolution of charge transfer—from femtoseconds to seconds—at the single-particle level (Fig. 1). These results provide in-depth insights into the efficient charge-transfer mechanisms underlying photocatalytic function and help identify bottlenecks in charge transfer that limit photocatalytic performance.

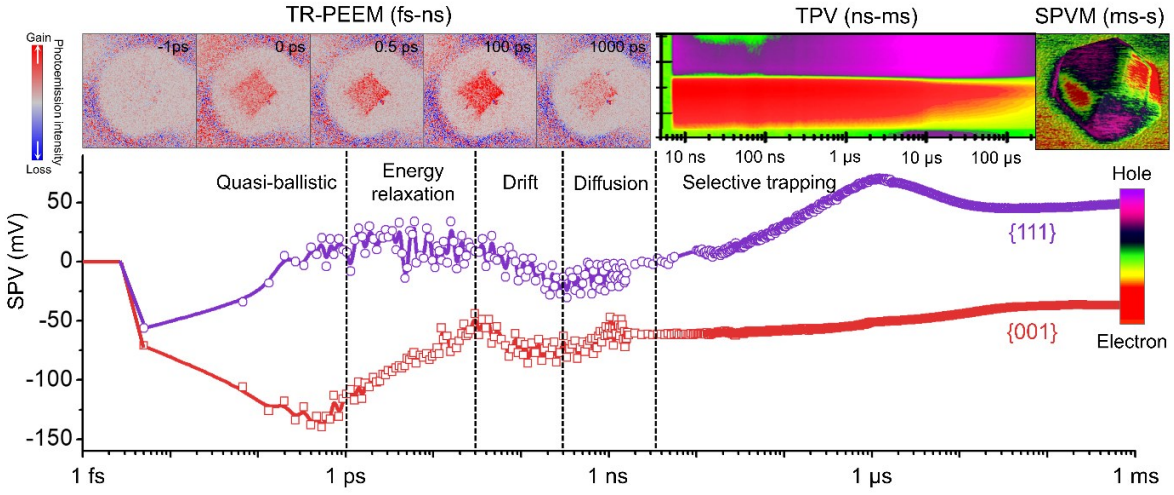


Fig 1. Spatiotemporal imaging reveals the holistic evolution of charge transfer in a single photocatalyst particle.

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Th-AM-09

4D-SEM for Spatiotemporal Imaging of Charge Carriers in Photocatalysis: From Femtoseconds to Steady-State

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This presentation introduces an advanced Dynamic Scanning Electron Microscopy (4D-SEM) framework tailored for the spatiotemporal imaging of charge carriers in photocatalysis, effectively spanning a comprehensive range from femtoseconds to steady-state conditions. By integrating transient optical techniques with dynamic electron microscopy, we achieve depth-resolved, real-space visualization of carrier populations1. This innovative approach enables the precise disentanglement of bulk versus surface dynamics, offering a clearer understanding of the underlying processes.2

We will demonstrate how these multimodal capabilities not only reveal critical transport bottlenecks and interfacial recombination pathways but also provide insights into the temporal evolution of charge carrier behavior. The integration of time-resolved measurements with spatial resolution facilitates the exploration of transient phenomena occurring at various timescales, thus establishing 4D-SEM as a powerful diagnostic tool. This framework is instrumental for the rational design of next-generation photocatalytic materials, enabling researchers to optimize performance by comprehensively understanding the interplay between charge dynamics, reaction kinetics and material properties. Through this presentation, we aim to highlight the transformative potential of 4D-SEM in advancing photocatalytic research and innovation.

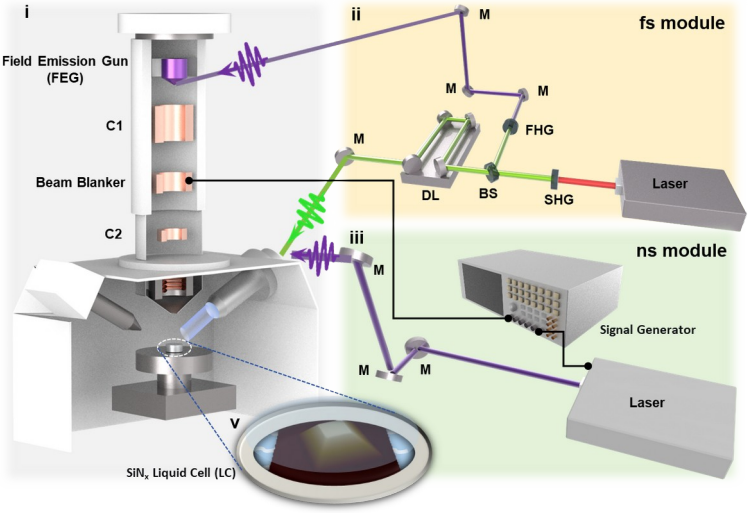


Fig 1. The setup of 4D-SEM with detection time window that ranges from sub-picoseconds to seconds.

Reference(s)

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Th-PM-01

Coherent Band Engineering in a Bimetallic 2D Metal-Organic Framework

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Two-dimensional metal-organic frameworks (2D MOFs) are atomically thin materials that combine the chemical versatility of organic molecules with the structural order of inorganic solids[1-2]. In this work, we realize a fully coordinated bimetallic framework by incorporating two transition-metal ions into a single coordination lattice. Using a tetracyanoquinodimethane (TCNQ)-based framework on Ag(100), we demonstrate that Ni and Co ions randomly occupy equivalent coordination sites while preserving long-range structural order.
Despite the random metal distribution, momentum microscopy measurements reveal a single well-defined dispersive π-d hybrid band that remains continuous across the Brillouin zone, demonstrating robust electronic delocalization within the framework. Strikingly, random metal occupation preserves electronic delocalization while enabling electronic tunability. Compared with the monometallic Ni-Ni-TCNQ$_1$ network, the bandwidth increases to ~1.6 eV (Fig. 1), accompanied by a change in the carrier effective mass. Notably, enhanced dispersion occurs without band splitting or fragmentation, indicating that the electronic structure evolves through a coherent average-potential mechanism analogous to semiconductor alloys[3].
These results establish fully coordinated bimetallic 2D MOFs as electronically tunable platforms in which bandwidth can be systematically engineered, extending key concepts of semiconductor alloy physics to molecular coordination solids.

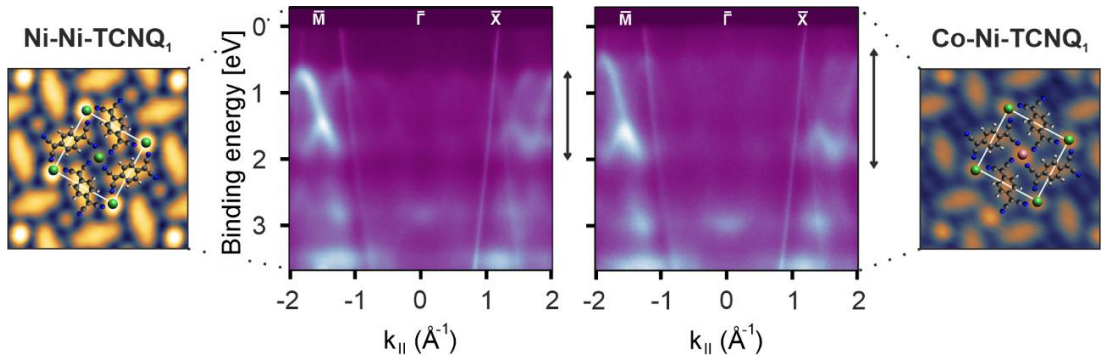


Fig 1. Constant-current STM images (3.0 × 3.0 nm²) of the monometallic Ni-Ni-TCNQ$_1$ and bimetallic Co-Ni-TCNQ$_1$ networks, acquired at $V = 1.0$V, $I = 100$pA and $V = 0.6$V, $I = 5.0$pA, respectively, together with momentum-resolved band maps measured along a high-symmetry direction of Ag(100), using p-polarized light at a photon energy of 30 eV[3].

Reference(s)

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Th-PM-02

Control of rotation and twist in bilayer graphene using novel faceted Cu growth substrates

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Chiral, high-index copper substrates have been reported to influence the orientation of monolayer graphene grown by chemical vapor deposition (CVD) [1]. However, the quantitative relationship between the substrate surface chirality and the graphene orientation has not been fully explored. Our work aims to gain a deeper understanding of this phenomenon and to extend previous work by developing a bottom-up approach to control the orientation and twist of bilayer graphene using these substrates. CVD graphene was studied on a series of samples with various orientations near the Cu(104). Low energy electron diffraction (LEED) and microscopy (LEEM) revealed that their surfaces are strongly facetted. The presence of (104) and (001) facets on all substrates and other facets that varied with the mean surface orientation was determined accurately by facet diffraction spot analysis [2]. Systematic variations of the facet morphology with surface orientation were also revealed by LEEM (Fig. 1). The top graphene layer is rotated clockwise or counterclockwise by angles $\pm\theta + \varepsilon$ with respect to the $[40\bar{1}]$ direction in the Cu(104) plane. Interestingly, the graphene orientation is biased uniformly by an angle ε that breaks the symmetry between opposite rotations. Furthermore, the symmetric component, θ, and the bias angle, ε, vary systematically with the deviation of the surface orientation from (104). The unusual bias angle appears to be determined by the chirality of the substrate surface, which is manifested by the orientations of the highly elongated (001) facets (yellow arrows in Fig. 1) and the facets that span the (104) areas between (001) facets. A modest systematic variation of bilayer twist with substrate orientation of up to 2 degrees will also be described. These observations demonstrate the potential for controlling bilayer graphene orientation and twist using chiral, high index Cu substrates.

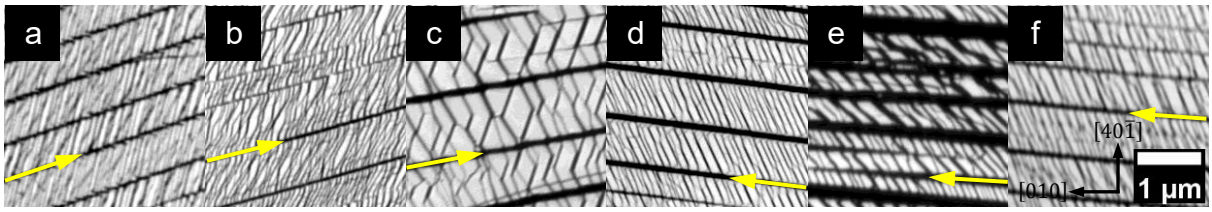


Fig 1. LEEM images of bilayer graphene on Cu samples with mean surface orientations that vary systematically (l to r) away from (104) (located between (c) and (d)). The common facets are (104) (bright) and (001) (dark indicated by yellow arrows). Facets that span the (104) between the (001) facets (dark) vary among the samples. The orientations of these facets, "/" in (a), (b), "\" in (d)-(f), mixed "/" and "\" in (c) and the (001) facet orientations, manifest substrate chirality.

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Th-PM-03

Rise and fall of 1T-TaS_2: Epitaxial growth of monolayer TaS_2 on Au(111)

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Group V transition metal dichalcogenides (TMDs), such as TaS_2, have attracted extensive research interest for their ability to exhibit electron-correlation effects, including charge density waves (CDWs). In particular, 1T-TaS_2 is of significant interest because it exhibits a CDW at room temperature. However, when grown on metal substrates, only 2H-TaS_2 has been reported [1]. To address the apparent lack of 1T-TaS_2 growth in the literature, we have investigated the growth of TaS_2 on Au(111) under ultra-high vacuum conditions using *in-situ* low-energy electron microscopy (LEEM), micro-diffraction (μLEED), and X-ray photoemission electron microscopy (XPEEM) [3]. We show that, at elevated temperatures, TaS_2 nucleates and grows in two distinct phases, identified by bright and dark contrast in LEEM (Fig. 1(a)). The metastable bright phase nucleates first and governs overall areal growth, eventually transitioning into the dark phase via a temperature-activated process. XPEEM reveals that, despite comparable Ta amounts within the islands, the islands exhibit distinct Ta4f core-level spectra, giving rise to chemical contrast (Fig. 1(b)). The XPEEM spectra show excellent agreement with the reference spectra of 1T-TaS_2 and 2H-TaS_2 [2] (Fig. 1(c)), enabling the identification of the bright phase as 1T-TaS_2 and the dark phase as 2H-TaS_2. This assignment is further supported by μLEED. We find the same growth behavior for $TaSe_2$/Au(111) under similar experimental conditions, indicating a general growth mechanism.

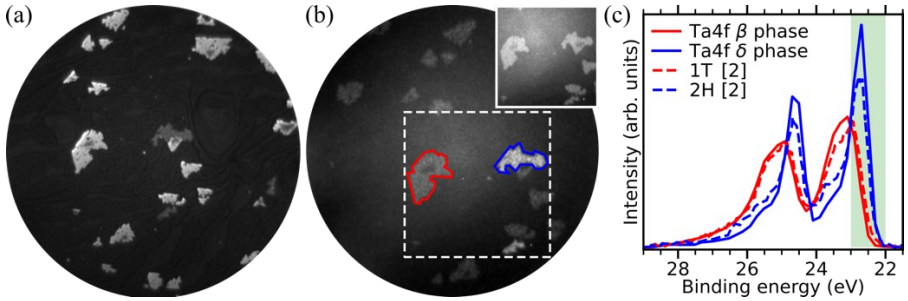


Fig. 1. (a) LEEM image of TaS_2/Au(111) showing two TaS2 phases distinguishable by bright and dark contrast. (b) XPEEM image of the same region, integrated over the Ta4f peak (22-23 eV binding energy). Inset: integrated Ta4f intensity. (c) XPEEM spectra extracted from the bright (β phase, red) and dark (δ phase, blue) phases in (a).

Reference(s)

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Th-PM-04

Micro-ARPES visualization of strain-induced metallic state in 1T-TaS_2

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The insulating state of 1T-TaS_2, long regarded as a strongly correlated Mott insulator [1], has recently been reinterpreted as a band insulator arising from interlayer dimerization [2]. This debate places the interlayer stacking degree of freedom at center stage and raises a fundamental question: can novel electronic phases be engineered by actively tuning interlayer coupling?

Using micro-focused angle-resolved photoemission spectroscopy (micro-ARPES) supported by first-principles calculations, we demonstrate that uniaxial strain (up to ~1%) drives 1T-TaS_2 from its insulating charge-density-wave (CDW) phase into a stable, reversible metallic phase under equilibrium conditions, while the in-plane Star-of-David lattice is preserved. In the insulating CDW phase (T = 40 K), the Ta 5*d*-derived band forms an energy gap at the Fermi level (E_F), whereas under uniaxial strain the band crosses E_F (Fig. 1). Comparison with calculations indicates that the metallicity originates from a strain-induced AL-to-L stacking transition that disrupts the interlayer dimerization. Moreover, the emergent band shows a mass renormalization factor of about 2, identifying it as a strongly correlated metal near a Mott transition. Our results establish uniaxial strain as a selective tool for tuning interlayer coupling in 1T-TaS_2, opening new pathways for exploring hidden quantum phases in two-dimensional materials.

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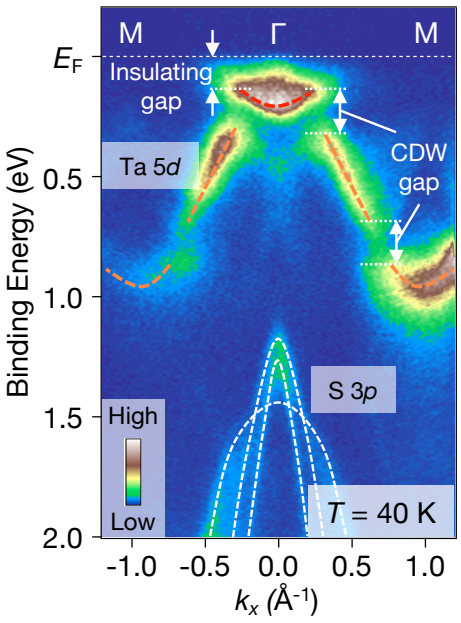


Fig 1. ARPES-intensity plot along the ΓM direction measured in the insulating CDW phase (T = 40 K) of 1T-TaS_2 without uniaxial strain.

Th-PM-05

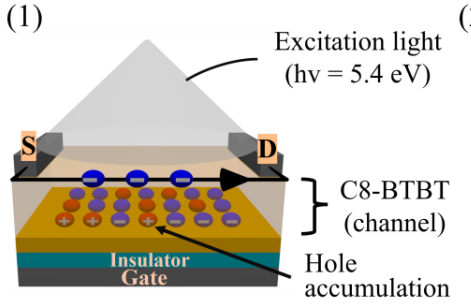
Real-space visualization of conductive holes in organic transistors by operando photoemission electron microscopy

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The concept of holes was introduced by Peierls in 1929 as virtual positive charge carriers arising from the absence of an electron [1]. Since then, the properties of holes have generally been investigated using electrical techniques such as current–voltage and Hall effect measurements. In this study, we performed real-space imaging of conducting holes in organic field-effect transistors (OFETs) using operando photoemission electron microscopy (operando-PEEM) [2].

Figure 1 shows a schematic illustration of the employed p-type OFET, where a C8-BTBT film was used as the channel layer. When a negative gate voltage (V_G) is applied, holes are injected from the source (S) and flow along the channel/insulator interface, resulting in the drain current (I_D) characteristics (black plots in Figure 2). To extract photoelectrons from this interface, the C8-BTBT thickness was restricted to less than 10 nm owing to the short escape depth of photoelectrons. PEEM images were acquired concurrently with the I_D measurements. Representative images at V_G = 0 V and −8 V in Figure 2 show that the C8-BTBT channel becomes darker as V_G decreases, reflecting the injection of conducting holes. The V_G dependence of the PEEM intensity (blue plots in Figure 2) extracted from the entire channel (blue square in the PEEM images) is also plotted. Importantly, the change in PEEM intensity well agrees with the variation in I_D, indicating the successful real-space imaging of hole accumulation during transistor operation. This method can unveil carrier transport mechanisms in diverse semiconductors, advancing future devices.



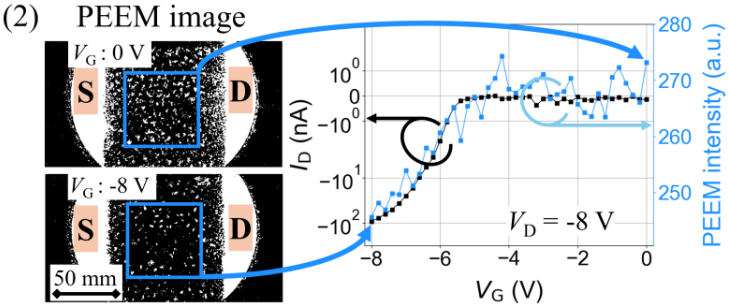


Figure 1. Schematic of the p-type OFET. **Figure 2.** Operando-PEEM images measured at V_G = 0 and −8 V, and variations in the PEEM intensity and I_D as a function of V_G in the C8-BTBT transistor.

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Th-PM-06

Thermionic emission and Work Function modulation on $BaWO_4$

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Barium tungstate ($BaWO_4$) is a promising material in the field of photonics due to its optical transparency, high dielectric permittivity, high stability and its insulator behaviour. In previous works [1] we have reported the growth of $BaWO_4$ islands by Molecular Beam Epitaxy (MBE) by depositing Ba and taking advantage of the reactivity of the W(110) surface under exposure to oxygen to provide a source of tungsten cations. This method produces highly-crystalline isosceles triangular islands of $BaWO_4$, tens of nanometers thick and tens of micrometers wide.

While heating above 700 C, these nanostructures exhibit thermionic emission. We have obtained sharp and clear Thermionic Emission Microscopy (ThEEM) images with just the electrons that come from the heated sample. Furthermore, we have observed that the intensity of the ThEEM images changes depending on the islands atomic termination, that can be changed by additional barium deposition or oxygen exposure.

In this talk we will explore both the growth of $BaWO_4$ nanoislands and their characterization by various microscopy methods and the dependency on the thermionic emission and work function with the surface termination.



Fig 1. ThEEM image at 700 C, FOV=30μm

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Th-PM-07

Probing Hyperbolic Plasmon Polaritons and Resonances in $MoOCl_2$ by TR-PEEM

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Femtosecond time-resolved photoemission electron microscopy (TR-PEEM) has broad applications in nanophotonics and surface physics due to its nano-femto spatiotemporal resolution. The applications of PEEM in nanophotonics started from surface plasmon polaritons/resonances (SPPs/SPRs) supported by metals, about twenty years ago, which have experienced successful developments. However, previous PEEM studies have mainly focused on noble metals, limiting the applications to a broader family of materials and modes in nanophotonics. Therefore, it is necessary to expand the scope of nanophotonic research based on PEEM. In this talk, I will present our recent work on imaging optical near-field modes of van der Waals (vdW) materials using PEEM. This talk will focus on imaging hyperbolic plasmon polaritons[1] and hyperbolic localized plasmons[2] supported by a novel vdW material, MoOCl2. These studies demonstrate that PEEM has broad prospects in the investigation of near-field optical modes beyond conventional metals.

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Th-PM-08

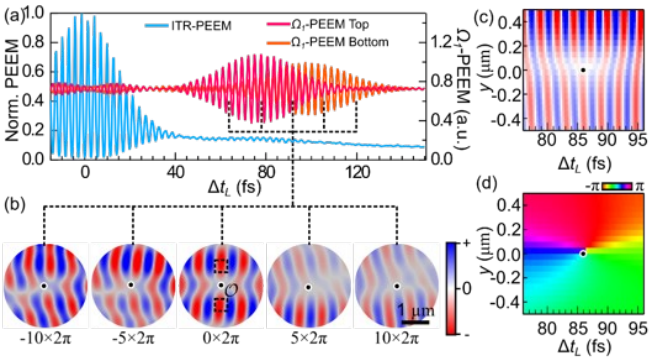
Nano-atto Imaging of Spatiotemporal Plasmonic Vortices on Chip

Qian Chen[1], Shuoshuo Zhang[2], Xian Guoyu[3], Haoqiang Hu[1], Xiaohua Wu[1], Xiaofei Wu[4], Jer-Shing Huang[4], Chen-Bin Huang[5], Jin-hui Zhong[6], Yunquan Zhang[2], Xiaocong Yuan[2], Changjun Min[2], Yanan Dai[1]

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Interferometric time-resolved photoemission electron microscopy (ITR-PEEM) makes it possible to watch optical near fields as they move, interfere, and reshape at a surface. Here, we use this capability to create and image spatiotemporal plasmonic vortices (STPVs) on metallic chips. In contrast to conventional plasmonic vortices, whose singularities are mainly arranged in space, STPVs are ultrafast surface-wave packets in which the phase winds through both space and time. We generate them by launching temporally delayed plasmonic eigenmodes from designed coupling structures, converting a space–frequency phase defect into a propagating spatiotemporal vortex. ITR-PEEM captures this process as a nanoscale movie while resolving the quantum pathways of coherent two-photon photoemission that encode the nonlinear plasmonic response. This pathway sensitivity reveals the vortex-core motion, phase evolution, focus-induced reversal, and harmonic angular-momentum conversion. More broadly, this work shows how structured surface waves can be programmed not only in space, but also in time, providing a route toward active ultrafast near-field control and topology-guided light–matter interactions.



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Th-PM-09

PEEM based near-field imaging of plasmonic topological nanochains

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Photoemission electron microscopy (PEEM) with ultrahigh spatial-temporal resolution can be a good platform to measure the plasmonic modes in the near field and the time field1. We have successfully explored the near-field mode distributions and the topological dynamic responses of topological edge states (TESs) in the Aubry-André-Harper (AAH) nanochains. The wavelength-dependent mode distributions of AAH chains are well demonstrated by PEEM instruments, which provides a reliable approach for the multidimensional regulation of TESs and explains the dynamic evolution process of TESs from a fundamental physics perspective.

Here, we report a novel strategy of weaving gold nanodisks with waveguides to realize an ultracompact on-chip-integrated plasmonic topological insulator with an AAH configuration2. The on-chip plasmonic topological insulator is constructed by gold nanodisks that are connected by short gold waveguides with different widths, meeting the extremely strict precision requirement of coupling parameters for sample nanofabrication and suppressing the influence of plasmon hotspots. Furthermore, we discover a transition between symmetric and asymmetric boundary modes of the plasmonic topological nanodisk chains with increasing nanochain length, corresponding to variations in the value of parameter ϕ of AAH model. This work advances the foundational research and practical applications of controlling synthetic dimensions in optical micro/nano-scale AAH models, providing robust support for the development of plasmonic topological photonics. By addressing the challenges in this field, the work lays a foundation for the development of advanced photonic devices and information processing chips, enabling further exploration and innovation in the realm of topological photonics.

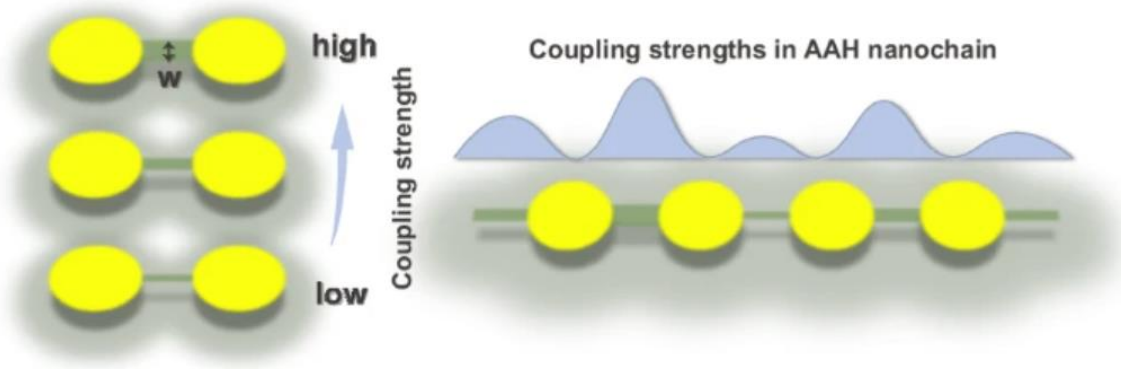


Fig 1. Schematics of dimer-waveguide configurations. The coupling strength between nanodisks increases as the connecting waveguide width increases.

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Th-PM-10

Linking extended vector wave fields with momentum space topology

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The success of topology in physics is based on its ability to describe complex physical systems through simple quantities: topological invariants. These invariants are integer-valued and remain unchanged under continuous deformations, making them highly attractive for robust technological applications. For infinitely extended wave fields, however, a global real-space topological classification is generally ill-defined unless the space can be compactified. Here, we use time-resolved polarimetric photoemission electron microscopy [1,2] to directly image the spatiotemporal vector-field dynamics of two-dimensional surface plasmon polariton fields and show that their topology is captured by a momentum-space linking number [3]. Our measurements reveal discrete transitions between distinct topological sectors in modes carrying fractional orbital angular momentum. By extending the linking-number formalism to discrete momentum spaces, we further classify periodic and aperiodic real-space fields, including plasmonic quasicrystals [4]. The experiments establish a direct connection between global vortex charge and momentum-space topology, and demonstrate time-resolved polarimetric photoemission electron microscopy as a powerful vector-field technique for the topological characterization of structured optical near fields.

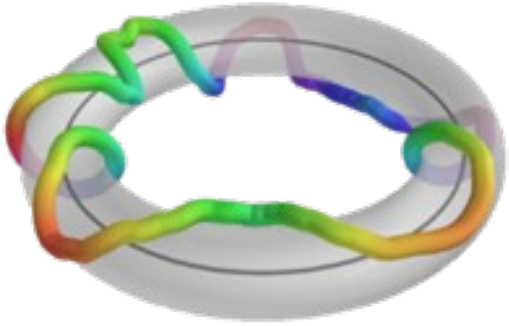


Fig 1. The phasor trajectory winds along the ring in momentum space, linking with the ring.

Reference(s)

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Fr-AM-01 Photoelectron Diffraction in the Minimum of the IMFP-Curve

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The full-field recording scheme of momentum microscopes makes them highly effective at capturing photoelectron diffraction (PED) patterns of core levels. The single-hemisphere based instrument [1] at the I09 soft X-ray beamline at the Diamond Light Source (Didcot, UK) can capture a core-level PED pattern in a large solid angle close to 2π, including its circular dichroism (CDAD) texture, in 5-10 minutes. This high recording speed enables the kinetic energy, E_{kin}, to be varied in 2 eV steps by varying the photon energy. An automatic scanning routine yields 3D data arrays $I(E_{kin},k_x,k_y)$. We have captured such 'PED movies' for the model systems Si 2*s*, 2*p* and Ge 3*p,* 3*d* at kinetic energies ranging from 250 to 35 eV, crossing the minimum of the *inelastic mean free path (IMFP)*. The measured diffractograms (Fig. 1 rows 1 and 3) reveal a complex structure that changes rapidly with kinetic energy, even in regions where the IMFP is only a few angstroms.

We find a good agreement of these measurements with one-step photoemission calculations (rows 2 and 4), which are based on fully relativistic density functional theory as implemented in the multiple-scattering *Korringa-Kohn-Rostoker (KKR)* Green's-function code SPRKKR [2,3]. The theory predicts features that are even finer than those observed in the experiment, with structured patterns extending to the photoemission threshold. At identical E_{kin}, significant differences are observed in the PED patterns for Ge 3*d* and 3*p*, as well as Si 2*s* and 2*p*. This emphasizes the importance of the orbital structure of the initial state. These calculated results bridge the gap between PED analysis and electronic structure investigations. Our approach maximizes the amount of information obtained from a PED experiment. It combines the '*large solid angle mode*', pioneered by Fadley [4], with the *'scanned-energy mode'* [5]. These results will be important for future femtosecond time-resolved PED studies using laboratory photon sources based on high-harmonic generation.

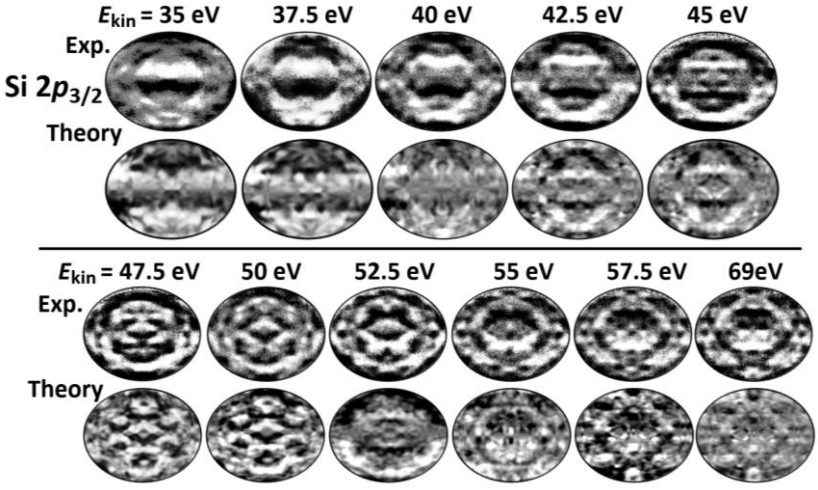


Fig. 1. Measured and calculated PED patterns at low kinetic energies. The panels show the CDAD contrast $A_{CDAD}= (I_{RCP}-I_{LCP})/(I_{RCP}+I_{LCP})$. $I_{RCP,LCP}$ denote the intensity patterns taken with right- and left-circular polarization.

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Fr-AM-02

Tritium Microscopy

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Adsorbed hydrogen plays a crucial role in catalytic reactions; however, its location and surface distribution are difficult to determine. Tritium (^{3}H), a radioactive isotope of hydrogen (^{1}H), undergoes β decay and emits high-energy electrons. By collecting and reconstructing these β rays, the surface distribution of hydrogen can be visualized. For this purpose, a photoemission electron microscope (PEEM) can be adapted to detect β rays instead of photoelectrons. The emitted electrons exhibit a broad kinetic energy distribution with relatively high energies (maximum 18.6 keV and mean 5.7 keV [1]). Their efficient collection is a key technical challenge. To address this issue, we employed a magnetic objective lens, enabling efficient collection of high-energy electrons. In addition, an energy filter was used to reduce the kinetic energy spread. Based on this concept, we developed an EXPEEM(energy filtered PEEM) system equipped with a magnetic objective lens and an eight-pole Wien filter, as shown in Figure 1.

As a proof of concept, tritium-labeled dextran (radioactivity: 1.54 MBq) was used as the sample. Figure 2 shows a PEEM image of dextran sample acquired with an accumulation time of 270 s, in which the bright regions correspond to the tritium-labeled dextran [2]. To the best of our knowledge, this is the first PEEM image obtained by directly collecting high-energy β-ray electrons from a tritium-labeled sample. Although further improvement in sensitivity is required for operando measurements, this approach establishes a new methodology for surface hydrogen imaging beyond conventional techniques.

Acknowledgement.

The authors acknowledge Dr. Norinobu Yoshikawa (Shiseido Co.) for providing the sample and Suga Co., Ltd. and Dr. Katsushige Tsuno for the construction of the EXPEEM system.

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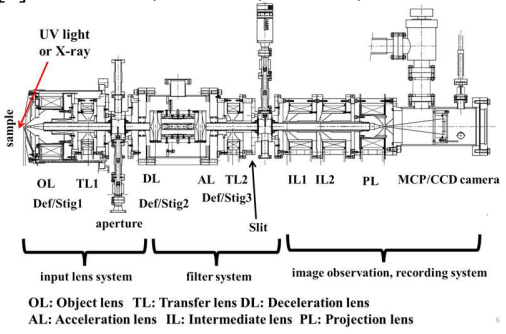


Fig.1 EXPEEM system

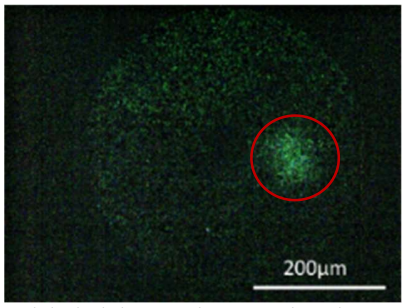


Fig.2 Tritium-labeled dextran image using the EXPEEM system.

Fr-AM-03

The QSPLEEM User Instrument: Time-Resolved, Low-Temperature, Angle-Resolved Studies of Magnetic Quantum Materials

Alexander Stibor[1*], Usama Choudhry[1], Nicholas Dale[1], Kevin Moseni[1], Sinéad Griffin[1], Cameron Johnson[1], Roberto Lo Conte[2]

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The dynamic characterization of heterogeneous quantum materials, such as 2D van der Waals magnets, altermagnets, and other spin-textured systems, is essential for understanding their structural and magnetic order, phase transitions, and ultrafast transport phenomena. These processes occur on nanometer length scales and picosecond timescales. We present new capabilities and recent developments of the Quantum Spin-Polarized Low-Energy Electron Microscope (QSPLEEM) at the Molecular Foundry, including a femtosecond-laser–driven pulsed spin-polarized electron source, a custom liquid-helium cryogenic sample stage, and the implementation of angle-resolved reflection electron spectroscopy (ARRES).
Two representative user experiments highlight the capabilities: The first employs ARRES, demonstrated on Iridium, where we visualize spin textures in momentum space; this method has also been applied to characterize a g-wave altermagnet [1]. Second, we investigate the magnetic domain structure and the emergent interlayer ferromagnetic coupling in thin flakes of the 2D material CrSBr on a gold thin film [2]. We also describe the integration of a femtosecond Ti:sapphire laser to generate ultrashort, polarization-controlled electron pulses, enabling future spin-polarized pump–probe LEEM, LEED and PEEM. Preliminary measurements quantify space-charge-induced distortions via LEEM I(V) curve broadening and use pump–probe work function shifts from a laser-induced surface photovoltage to estimate the electron pulse FWHM. These QSPLEEM upgrades open new opportunities for time-resolved studies of spin-dependent magnetic structures, mapping of spin-resolved unoccupied band structures, and nanoscale magnetometry at cryogenic temperatures.

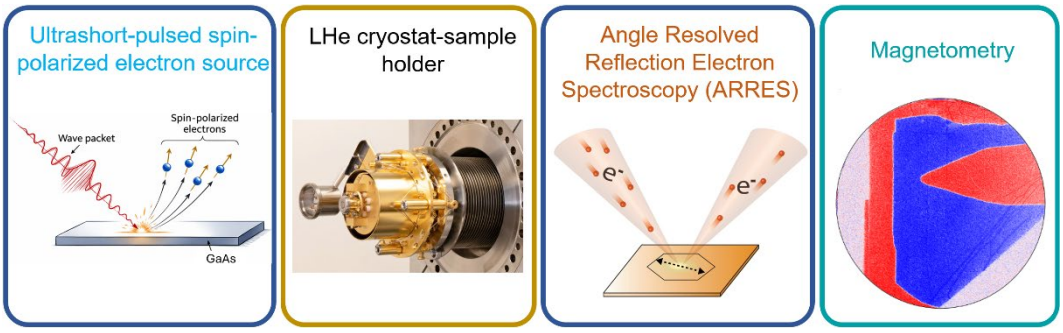


Fig. 1. Capabilities of the QSPLEEM user instrument.

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Fr-AM-04

Dynamic synthesis and characterization of large-area high-quality borophene on metal surfaces

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Borophene, a crystalline monolayer boron sheet, is a new two-dimensional (2D) quantum material, predicted to feature tunable structure, intriguing physics and to find applications in flexible electronics, energy storage, and catalysis. We report on the synthesis of large-area high-quality single-crystal borophene on various metal surfaces monitored in situ by low-energy electron microscopy (LEEM), diffraction and scanning tunneling microscopy(STM), and ex-situ by X-ray photoelectron spectroscopy and atomic force microscopy. By growing borophene on Cu(111) surfaces, we obtain large single-crystal domains, up to 100 μm2. The synthesis of borophene on a square lattice Cu(100) surface shows that incommensurate coordination could reduce the borophene-substrate interactions and alter the borophene structures in interesting ways. Micrometer-scale single-crystal domains can form as isolated faceted islands or merge to achieve full monolayer coverage. First-principle calculations indicate that charge transfer rather than covalent bonding binds 2D boron to the copper surface and confirms its integrity and uniformity The electronic band structure features multiple anisotropic tilted Dirac cones, heralding emergent quantum fermions.

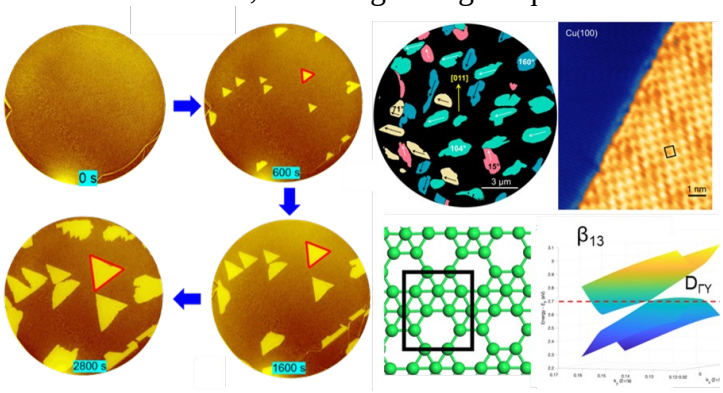


Fig 1. The growing process of borophene on Cu(111) and Cu(100) surface, and corresponding atomic and band structure

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Fr-AM-05

Oxidation of single-layer antimonene

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Wide-bandgap two-dimensional materials with high dielectric constants are expected to play an important role in future nanoscale electronic devices [1]. Antimony trioxide, with a band gap of 3.5 eV and a dielectric constant of $k = 6$, satisfies the key requirements of this class of dielectric materials.

In this contribution, we report the formation of a large-scale monolayer film of antimony trioxide. The synthesis begins with the preparation of a unique antimonene phase on a W(110) substrate. This phase consists of a single-atom-thick layer that is relatively strongly bonded to the W atoms and passivates the tungsten surface [2]. In the second step, a monolayer of α-phase antimonene is grown on top of this interfacial phase [3]. Both antimonene phases form large-scale films that uniformly cover the substrate.

The sample is then exposed to ambient conditions, resulting in oxidation of the top α-antimonene layer. Subsequent gentle annealing under ultrahigh vacuum restores the crystallographic order, yielding a crystalline monolayer of antimony trioxide. The oxide layer remains supported by the underlying interfacial antimonene phase, which is resistant to oxidation.

Acknowledgements
The work has been supported by the National Science Centre (Poland) under Grant No. 2024/55/B/ST11/01717.

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Poster Presentation

Oct. 7

17:00 – 18:30~

P-001

Effect of perovskite grain surface crystal facet orientation on the local photochemical stability

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Over the past decade, polycrystalline perovskite thin films have indisputably demonstrated their potential as a strong candidate for next-generation solar materials with the efficiency of a single junction perovskite solar cell now surpassing that of a silicon solar cell. However, despite their exceptional device efficiency, perovskite solar cell often suffers from low device stability and reliability. Being polycrystalline, a typical perovskite thin film is made up of grains with random distribution of surface crystal facets. These different surface crystal facets with unique atomic arrangement and coordination would result in distinct electronic and chemical properties that would in turn affect their interactions with external stimuli.

In recent years, there has been an increase in research activities [1-5] that aim to control the growth orientation of these polycrystalline perovskite thin films. The success in the growth of dominantly (100), (110), and (111)-oriented thin films has enabled systematic studies of facet-dependent optoelectronic properties and their corresponding impact on the device performance and stability. Here, we investigate the correlation between the tilt angle of the (100) surface crystal facets of individual perovskite grains and their photochemical stability upon photocarriers generation. We observed that, even in such a dominantly (100)-oriented perovskite thin film, as evidenced by the dominant (100) XRD peak, the comparatively small deviation in the tilt angle of the individual grains still leads to a vastly different photochemical characteristics, specifically the local generation of the I_3^- and the metallic lead species at specific crystal facets. These two chemical species are often related to the degradation process in perovskite thin films. Thus, an understanding of their facet-dependent photochemical evolution will allow for targeted facet-dependent engineering of the chemical stability of the surfaces of these polycrystalline perovskite thin films.

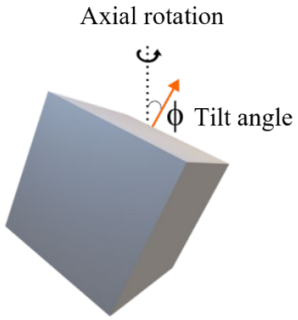


Fig 1. Schematic depicting the grain orientation with a tilted (100) surface facet.

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P-002

Quantitative comparison of the performance for three different LEEM-PEEM detector systems

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During 2025–2026, both Spanish LEEM-PEEM facilities—the ALBA Synchrotron and IQF-CSIC—upgraded their detectors: ALBA to a TimePix3-based hybrid pixel system, and IQF-CSIC to a fibre-coupled CMOS camera [1]. We acquired before-and-after datasets to quantitatively compare the new detectors with their MCP+CCD predecessors. Our analysis, based on unfocused flat-field images and noise scaling with spatial and temporal binning, provides a robust, alignment-insensitive comparison of intrinsic detector performance. The TimePix3 detector at ALBA achieves a 30–100% improvement in signal-to-noise ratio over the MCP-CCD [2], especially at low electron count rates, due to its direct electron detection, which minimize blooming and readout noise. Results for the new CMOS system at IQF-CSIC will be presented at the conference following its installation in July 2026.

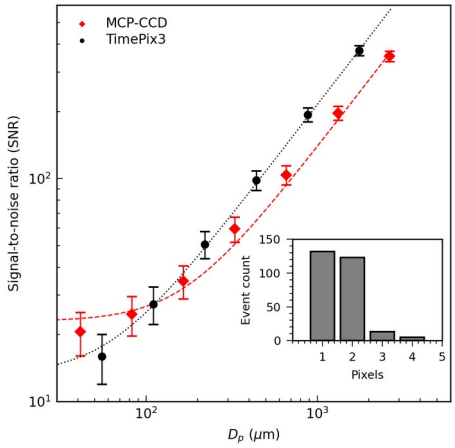


Fig 1. Signal-to-noise ratio as a function of spatial binning area. The TimePix3 (black) follows √N scaling (dashed line), while MCP (red) deviates at small areas due to blooming. Inset: histogram showing the number of pixels activated per 20 keV electron in the TimePix3 detector at low count rates.

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P-003

Experiments with Surface Acoustic waves (SAW) at the ALBA PEEM

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Surface acoustic waves (SAW) are elastic deformation waves in the upper layer of crystals. They have frequencies in the MHz-GHz range, micrometric wavelengths and propagate millimeters to centimeters. In piezoelectric substrates such as lithium niobate ($LiNbO_3$), SAW can be excited and detected by interdigitated transducer electrodes (IDT).

Using the ALBA synchrotron pulsed time structure (pulsed at 500 MHz), we have developed methods to excite, image and measure SAW in a PEEM instrument with full phase resolution. The sensitivity of the PEEM to the emitted electron kinetic energy provides a contrast mechanism through the associated surface potential oscillation which measures the SAW amplitude [1].

We apply these methods to study the effect of dynamic (subnanosecond) strain in different systems prepared over the $LiNbO_3$ substrates: delayed magnetic-domain-wall motion [2], long-range magneto-acoustic waves [3], including in antiferromagnets [4], and work-function oscillations in Pt [5] are examples of the results. The capabilities have been recently expanded to the GHz range by adding dedicated high-frequency contacts [6]. We will give an overview of the work done so far and provide an outlook to next developments.

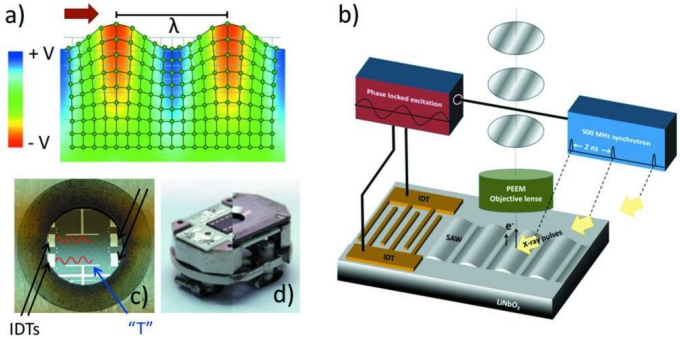


Fig 1. Schematic of a SAW (a) and the experimental setup. (b) Synchronization scheme providing phase resolved stroboscopic images. (c), (d) mounted sample (top view) and sample holder.

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P-004

Towards Multidimensional Coherent Spectroscopy in Photoemission Momentum Microscopy

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Photoemission momentum microscopy has emerged as a powerful tool for probing the electronic structure of quantum materials with high energy and momentum resolution. Combined with ultrafast pump-probe techniques, it provides direct access to the momentum-dependent nonequilibrium dynamics of electronic quasiparticles following optical excitation. However, disentangling the microscopic interactions governing these dynamics remains challenging, as such measurements primarily track transient quasiparticle populations.

Multidimensional coherent spectroscopy provides a complementary framework for resolving couplings and correlations underlying the coherent nonequilibrium dynamics of quantum many-body systems, yet typically lacks direct access to electronic states with energy and momentum resolution. Previous work has demonstrated the combination of multidimensional coherent excitation schemes with photoemission electron microscopy [1] and photoelectron spectroscopy [2] at surfaces. Building on these concepts, we explore their extension to time-resolved photoemission momentum microscopy, combining coherent multidimensional excitation with energy- and momentum-resolved photoelectron detection.

In such an implementation, Fourier transformations along the inter-pulse delays of the excitation sequence would introduce additional spectral dimensions that resolve and correlate the energies of participating excitations, while momentum microscopy would provide simultaneous access to the energy and momentum of photoelectrons generated via a subsequent photoemission probe pulse. This combination of techniques would provide access to interactions and correlations among electronic quasiparticles and elementary excitations across the electronic band structure. Ultimately, such capabilities establish a new route toward investigating coupled ultrafast dynamics and many-body interactions in quantum materials.

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P-005 Student

Spatiotemporal control of ultrashort-pulsed high-density electrons by radiofrequency, terahertz, and optical waves

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Electron beams are widely used for structural characterization of materials through diffraction, spectroscopy, and imaging techniques. By using pulsed electron beams, we have been developing an ultrafast time-resolved electron diffraction system, which enables direct observation of structural changes in materials under photoexcitation. However, electron beams are affected by space-charge effects, leading to a degradation of spatial and temporal resolution. To overcome this issue, we have developed spatiotemporal control of pulsed electron beams, such as compression, acceleration, deceleration, deflection, and defocusing. These techniques are expected to contribute to the establishment of flexible electron-beam control.

First, we performed pulse compression using RF waves. In ultrafast electron diffraction measurements, the temporal resolution is generally limited by the duration of the electron pulses. Therefore, pulse compression is an important technique. Utilizing this compression technique, pulsed electrons with an initial duration of more than 10 ps were successfully compressed to 200 fs. In addition, the pulse duration could be freely varied from 200 fs to 50 ps by adjusting the RF field strength. Second, we observed electron deflection by the THz waves. Although pulse compression improves the temporal resolution, achieving sub-100 fs resolution remains challenging. To further improve temporal resolution, the electron streak diffraction system [1], which converts temporal information into spatial information via deflection, is a possible approach. In this study, THz waves were irradiated onto an antenna-type resonator, generating an enhanced electric field (strength: 1 MV/cm). We observed that the electron beam was deflected in accordance with the THz waveform. This technique enables the development of a new electron streak diffraction system with a temporal resolution of 10 fs. Third, we demonstrated electron beam defocusing using an optical laser pulse (beam width (FWHM): 15 μm, pulse duration: 40 fs, center wavelength: 800 nm, fluence: 300 J/cm^2) through the ponderomotive interactions [2]. The electron beam width diverged by approximately 50 %. Multi-electron trajectory calculations in electromagnetic fields also revealed that the focusing and defocusing of electron beams can be controlled by manipulating the spatial laser modes (LG00 and LG01) [3].

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P-006

Structural and electronic properties of lead halide perovskite thin film surfaces

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Polycrystalline perovskite thin films are consistently associated with high performance photovoltaic devices. The main challenges currently under the spotlight lie with the stability and reliability of these devices, requiring a better understanding of the thin film surfaces and interfaces. However, very little is known about them. Given the soft nature of these materials, there is a struggle to directly assign the origin of the electronic features and to correlate them to the chemical nature of the surfaces. Here, by exploiting a multimodal approach, we measure for the first time, at sub-micron scales, the diffraction patterns of the thin film grain surface, which provide the material fingerprint and experimental evidence that the surface of such soft semiconductors is not as disordered and fragile as often claimed. Then, building on such knowledge, we move to ultraviolet photoemission spectroscopy (UPS), which provides information about the electronic structure of the first few nm of semiconductor thin films. Therefore, having proof of the structural nature of the surface under investigation, we are eventually able to unambiguously assign the origin of the photoemission spectra for a wide library of metal halide perovskites. In particular, metallic lead is identified to be the origin of the often-reported mid-gap photoemissive states, so far assigned to deep electronic states within the halide perovskite semiconductor band gap. The chemical composition of the metal halides, the photo-degradation of the perovskites under visible light, the quality of the precursors and the actual stoichiometry of the thin film heavily define the presence of such states and elucidates the origin of carrier loss, photo-degradation, and sample reproducibility in metal halide perovskites optoelectronics.

P-007

I06 LaserPEEM offline facility

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The I06 LaserPEEM/LEEM offline facility in Diamond, UK is a multidisciplinary nanoscience imaging facility housing a second PhotoEmission Electron Microscope (PEEM) equipped for Low-Energy Electron Microscopy (LEEM), micro focused-Low-Energy Electron Diffraction (μ-LEED) and Thresold PhotoEmission Electron Microscopy. Jointly funded by Diamond and EPSRC strategic equipment grant (EPSRC Grant: EP/V029258/1), the offline facility combines PEEM/LEEM with a continuous wave (CW) deep-UV laser source (wavelength 266 nm) providing high spatial resolution with probing depths ranging from less than a nanometre to tens of nanometres. The LaserPEEM/LEEM instrument provides unique opportunities to connect structure to function through detailed nanoscale imaging and real-time monitoring of, for example, catalytic chemistry on and around nanoparticles, ferroic domain walls manipulation, edge state structural modifications in 2D materials, battery electrode degradation, photovoltaic cell activity, etc.



Fig 1. Lab overview of I06 LaserPEEM facility.

Sm_2O_3 Nanoislands on Cu(111) and Their Polymorphic Behavior

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To understand the role of Sm doping in ceria reduction and the stabilization of active Ce^{3+} states for CO_2 hydrogenation [1,2], it is essential to investigate the interaction of Sm_2O_3 with the substrate to gain deeper insights into the Sm/CeO_x/Cu(111) model system [3]. Here, a multi-method approach is employed to study epitaxially grown, Cu(111)-supported Sm_2O_3 nanoislands with local structural and chemical sensitivity, combining LEEM and its complementary techniques, micro-spot diffraction and intensity-voltage LEEM, with XAS-PEEM and STM. Our measurements show that needle-like Sm_2O_3 structures begin to grow in three distinct directions from initially nucleated hexagonal Sm_2O_3(0001) nanoislands at 500°C. Upon encountering obstacles, such as other Sm_2O_3 islands or larger step edges, these structures expand laterally perpendicular to their growth direction, forming metastable, (100)-oriented monoclinic, rectangular-shaped Sm_2O_3 nanoislands that predominate the surface coverage of oxygen-rich Cu(111). Oxidation-state mapping of the coexisting hexagonal and monoclinic Sm_2O_3 phases reveals a homogeneous distribution of Sm^{3+} species with no indication of Sm^{2+}. Variations in deposition temperature, as well as post-annealing of grown Sm_2O_3 nanoislands, induce highly dynamic polymorphic phase transitions between hexagonal, monoclinic, and cubic Sm_2O_3 within a narrow temperature window.

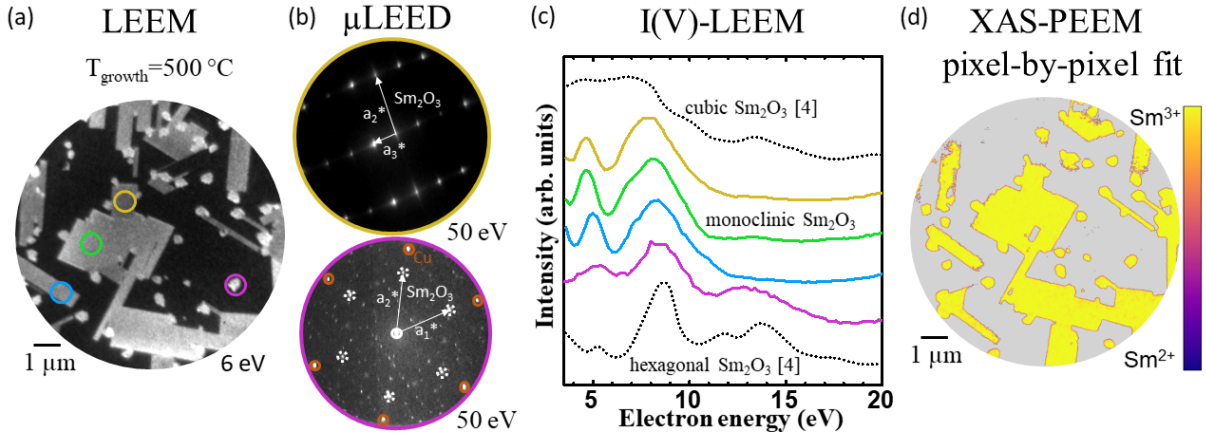


Fig 1. (a) LEEM image of as-grown Sm_2O_3 on Cu(111). (b) Micro-spot diffraction and (c) I(V)-LEEM curves of samaria nanoislands taken from the highlighted areas in (a). (d) Pixel-wise oxidation-state mapping of Sm^{3+}/Sm^{2+} from XAS-PEEM data at the Sm $M_{4,5}$ absorption edge.

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P-009

PEEM for high throughput brain mapping

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PEEM has the potential to become a powerful tool for high-throughput 3D nanoscale imaging of biological material. We present our progress on developing PEEM for imaging ultrathin, epoxy-based brain slices at imaging rates faster than any other electron microscopy approach in the world. We highlight key advances to making commercial PEEMs faster including: 1) laser integration for brighter illumination, 2) automation of stage movements and focus, and 3) integration with ion milling systems. These advances pave the way for creating a new use-case for PEEM in life science research and enable biological discovery in new and transformative ways.

P-010

Angle-resolved photoemission spectroscopy for polycrystalline materials

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Profound knowledge of electronic structures is essential for understanding electron behavior in materials and devices and for improving their performance. Angle-resolved photoemission spectroscopy (ARPES) is a powerful technique because it directly reveals the electronic band structure. However, the applicability of conventional ARPES is often limited by the requirement for large single crystals. Newly developed materials are typically available only as polycrystalline samples, while the growth of large single crystals requires significant time and effort.

Recently, microscopic techniques have become increasingly important in photoemission spectroscopy. While microscopic ARPES is usually realized by focusing the incident light, we have developed a microscopic ARPES system combining a photoemission electron microscopy (PEEM) lens system with an imaging-type double-hemispherical energy analyzer. The system achieves a spatial resolution of 40 nm in real-space imaging[1] and enables microscopic ARPES measurements using a vacuum-ultraviolet (VUV) laser source[2]. Furthermore, the incorporation of a two-dimensional Au/Ir spin filter enables highly efficient spin-resolved measurements[3].

Because polycrystalline materials consist of numerous microscopic single-crystalline grains, microscopic ARPES offers a promising approach for investigating their electronic structures. To demonstrate this capability, we applied our microscopic ARPES system to a commercially available polycrystalline silver sample.

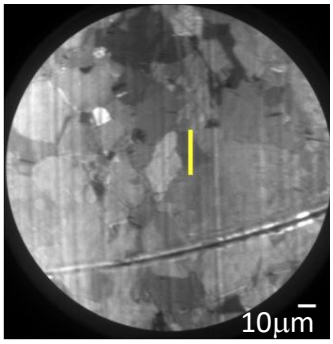


Fig 1. Real space image of polycrystalline silver

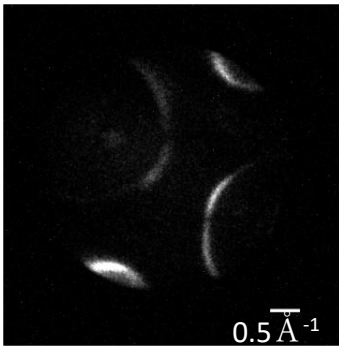


Fig 2. photoemission intensity map of polycrystalline silver at Fermi energy

Figure 1 shows a real-space image of the polycrystalline silver surface with a field of view of approximately 150 μm. The image exhibits regions with different intensities, originating from differences in crystal orientation among individual grains. By selecting a single grain, we successfully obtained an ARPES spectrum, as shown in Fig. 2.

In the presentation, we will discuss the experimental results in detail and introduce the analysis method used to determine the crystallographic orientation of the measured grains[4].

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P-011 Student

High-coherence time-resolved electron diffraction for capturing ultrafast intertube dynamics in carbon nanotube bundles

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Carbon nanotubes (CNTs) have attracted significant interest as promising materials for next-generation nanodevices. For practical electronic applications, they are typically engineered into bundled or highly aligned configurations. However, in such highly integrated assemblies, inter-tube van der Waals interactions can alter or degrade the overall electrical and thermal properties. While previous studies have reported ultrafast carrier and phonon dynamics within a single CNT[1], a direct understanding of these macroscale, collective characteristics in assembled structures remains limited. Therefore, understanding these collective characteristics is crucial. Ultrafast time-resolved electron diffraction (UED) based on optical pump-probe techniques has emerged as a powerful tool for tracking the ultrafast photoinduced responses of materials by capturing diffraction patterns before and after photoexcitation. In conventional UED setups, electron pulses are generated via the photoelectric effect from plate-type photocathodes, which typically limits the transverse coherence length (L_c) to approximately 1–2 nm. L_c serves as a critical indicator of the maximum structural periodicity observable in diffraction experiments. Conventional setups cannot capture the structural dynamics of CNT bundles possessing periodicities spanning several nanometers. Generally, electron beams emitted from a point source exhibit exceptionally high transverse coherence. Therefore, we developed a high-coherence UED setup utilizing a sharp tungsten tip with a 1 μm diameter as a point-source photocathode. This approach successfully enhanced L_c to over 10 nm [2]. Here, we report the direct observation of ultrafast structural dynamics within the long-period regime characteristic of CNT bundles.

The sample was a highly aligned, multi-walled CNT sheet. The sample was photoexcited with an optical pump pulse (515 nm) polarized parallel to the tube axis. Sector-selective analysis of the diffraction patterns revealed two distinct structural changes following photoexcitation. First, we observed a fast heat diffusion process along the tube axis rather than the radial direction on an ultrafast timescale. Second, we successfully observed that the entire tube alignment was disordered and then returned to its original state with a time constant of approximately 300 ps, consistent with our molecular dynamics simulations. These findings demonstrate that the developed high-coherence UED is a powerful tool for tracking long-period structural dynamics. As an outlook, we plan to investigate structures with large periodicities, such as moiré superlattices and/or proteins.

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P-012

Hard X-ray PEEM at PETRA III P22: Local Chemical Spectroscopy of Buried and Microstructured Materials

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Hard X-ray photoelectron emission microscopy (HAXPEEM) combines the chemical-state sensitivity of X-ray photoelectron spectroscopy with full-field photoemission microscopy and the increased information depth enabled by hard-X-ray excitation. At PETRA III beamline P22, HAXPEEM is implemented within a dedicated HAXPES environment providing tunable photon energies in the 2.4-15 keV range, high photon flux, flexible focusing optics, and variable X-ray polarization [1]. The instrument is based on an energy-filtered NanoESCA-type microscope adapted for photoelectron kinetic energies up to 10 keV, enabling bulk-sensitive spectromicroscopy with sub-micrometer lateral resolution [2]. Instrumental tests demonstrated selected-area spectra from regions below 500 nm, about 410 nm lateral resolution on an Au/Si test structure, and chemical imaging of buried SrTiO3 through a 7 nm Au overlayer [3].

The central aim of this contribution is to present a transferable workflow: a set of fiducial markers deposited on the sample surface enables reliable relocation of the measured region; HAXPEEM image stacks at selected core levels are converted into local XPS spectra; high-resolution HAXPES spectra provide a reference model for local HAXPEEM fitting, including component assignment, binding energies, line shapes, and fitting constraints; and co-registration with SEM/EBSD or complementary microscopy assigns the resulting chemical-state maps to microstructural features. Optional re-measurement of the same region before and after external treatment further allows local chemical changes to be followed directly. In compact form, the method can be described as markers → HAXPEEM stacks → local spectra → SEM/EBSD correlation → microstructure-resolved chemistry.

Published corrosion-related studies will be presented as methodological examples. In duplex stainless steel, HAXPEEM combined with EBSD enabled non-destructive comparison of surface films on individual ferrite and austenite grains before and after electrochemical polarization [4]. Related work on martensitic tool alloys extended the approach to microstructure-dependent oxide-film inhomogeneity associated with matrix regions, nitrides, carbides and tempering-induced features [5]. The broader aim is to show how P22 HAXPEEM complements spatially averaged HAXPES whenever local chemistry is governed by microstructure. Finally, we outline future application fields, including device-relevant multilayers, interface studies under controlled pre- and post-treatment conditions, and possible magnetic contrast experiments exploiting the hard-X-ray probing depth and variable polarization available at P22.

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P-013 Student

Towards studying quasiparticle interactions on the nanoscale

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Time-resolved photoemission electron microscopy (tr-PEEM) is a uniquely powerful tool for probing ultrafast electron and quasiparticle dynamics with nanometer spatial resolution [1]. However, studying nonlinear photoemission processes often requires high local light intensities to achieve a sufficient signal-to-noise ratio. As a result, the measured signal consists of overlapping contributions from single- and multi-particle processes, each with distinct dynamics, making it highly challenging to disentangle pure single-particle dynamics from the measured signal.

To address this limitation, we report our progress in adapting the intensity cycling technique, recently developed by our group [2,3], to tr-PEEM. By systematically varying the excitation intensity and taking specific linear combinations of the measurement data, this method enables the experimental separation of individual perturbative orders in nonlinear light–matter interaction. In this way, the signal contribution of N interacting particles can be isolated from the rest of the signal.

In our setup [4], we employ a 680 nm pump pulse with variable intensity for excitation, followed by a 340 nm probe pulse. This scheme allows us to investigate organic thin films, focusing primarily on probing ultrafast exciton dynamics. We demonstrate that intensity cycling enables the extraction of lower-order signals that reflect the pure single-particle exciton dynamics, most clearly demonstrated by revealing unobscured energy transfer dynamics at early delay times. Furthermore, the extracted higher-order signals provide insight into complex interaction dynamics, such as exciton–exciton annihilation, which serves as a probe for exciton diffusion. While achieving a comprehensive understanding of these higher-order processes is part of ongoing work, our preliminary results highlight how this approach expands the analytical capabilities of tr-PEEM, offering a robust method to disentangle complex, overlapping interaction dynamics.

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P-014

Progress in Photoelectron Momentum Imaging

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We present the *Impetus Momentum and Imaging Microscope* (Impetus MIM), which combines a hemispherical analyser capable of sub-meV resolution [1] and a novel entrance lens that enables several different operating modes [2,3]. Photoelectron momentum microscopy (MM) is a powerful alternative to classical angle-resolved photoemission spectroscopy (ARPES) and photoelectron diffraction (PED) for energies ranging from the vacuum ultraviolet to hard X-rays. MM captures (k_x,k_y) momentum images with diameters ranging from 2 to 12 Å^{-1}. We have achieved an angular resolution of 0.03° [4] and an energy resolution of 4.2 meV [5], with potential for further improvement.

This novel objective lens has been used in several experiments involving high harmonic generation (HHG) sources, synchrotrons and free-electron lasers (FELs) [3]. The electric field at the sample surface can be shaped from accelerating (similar to that of a conventional PEEM) to a zero or retarding field (see Fig. 1(a, b)). We illustrate examples of all operating modes. Retarding fields effectively reduce the space-charge interaction by redirecting slow electrons back to the sample. This 'repeller mode' is useful for ARPES at high energies and for time-resolved experiments with intense pump pulses. Space-charge suppression has been demonstrated at the FEL FLASH [6] and HHG sources [7,8].

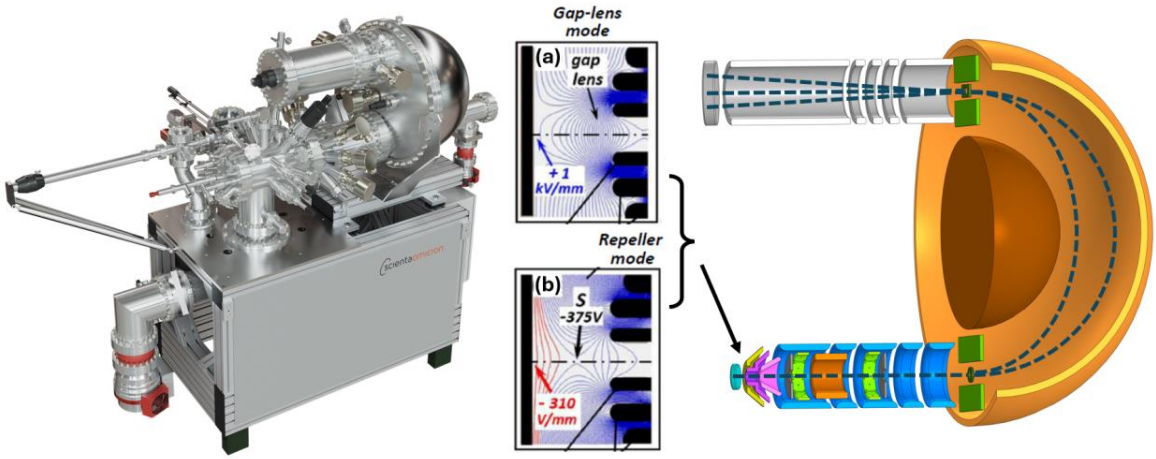


Fig 1. View and scheme of the Impetus MIM. (a) and (b) show two modes of the objective lens.

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P-015

Observation of exciton formation from free carriers in monolayer WSe_2 via a time-of-flight momentum microscope

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Recent developments of a time-of-flight momentum microscope (ToF-MM) combined with femtosecond laser sources have enabled the investigation of photoexcited unbound and bound electron–hole states in time, energy, and momentum spaces, even in few-micrometer-sized monolayer samples [1]. Here, we performed TR-ARPES on a monolayer WSe_2 using a ToF-MM to visualize the energy- and momentum-resolved dynamics during the formation of bound excitons from unbound states, as shown in Fig 1. We observed the momentum dynamics of intraband scattering of free carriers along the conduction bands immediately after photoexcitation with 3.1 eV pump pulses, followed by exciton formation from free carriers at delays later than 0.3 ps. In this talk, we will further discuss the timescale and microscopic mechanism of the scattering processes governing the transition from unbound free carriers to bound excitons.

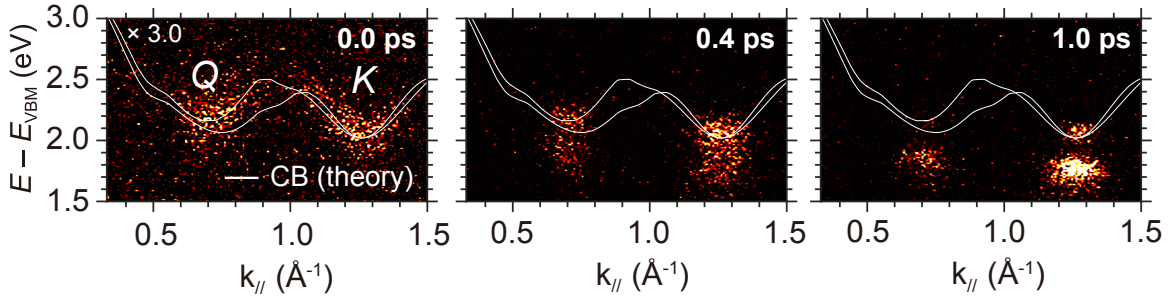


Fig 1. TR-ARPES spectra of the monolayer WSe_2 around conduction bands (CB) at the delays of 0.0 ps, 0.4 ps, and 1.0 ps. White solid lines indicate theoretical CB curves.

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P-016

LEEM Image Formation Theory: Principles and Applications

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Instrumental advances, such as aberration correction, have enabled new capabilities to characterize advanced materials using low energy electron microscopy (LEEM) and photoemission electron microscopy (PEEM). Capitalizing on these capabilities can also benefit from advances in our understanding of image formation and contrast. Fourier optics (FO) and contrast transfer function (CTF) are closely related theoretical approaches that have been adapted to model image formation in conventional and aberration-corrected LEEM [1-3]. These approaches have also recently been updated for field emission sources used in state-of-the-art LEEM instruments [4]. Although a simplification used in the CTF approach advantageously leads to its computational efficiency, a comparison of the CTF and FO approaches identified factors that can undermine the validity of the former, particularly with increasing defocus [5]. Consequently, the quantitative evaluation of image contrast, which is performed by comparing experimental and simulated through-focal image series, can only be done reliably using the rigorous FO approach. To facilitate this practical application of FO, the relationship between the experimental defocus current of the objective lens and the defocus distance used in FO image simulations has been established [6]. This approach has been used to determine (Fig. 1) the amplitudes of a ridge-groove surface morphology on a strained MnAs film [7] and periodic ripples in free-standing graphene [5], instrumental source divergence by modeling of high-order phase contrast at atomics steps on Ag(111) [8], and the inclinations of small angle facet boundaries on the NiO(100) surface that terminate bulk antiferromagnetic domains walls [9].

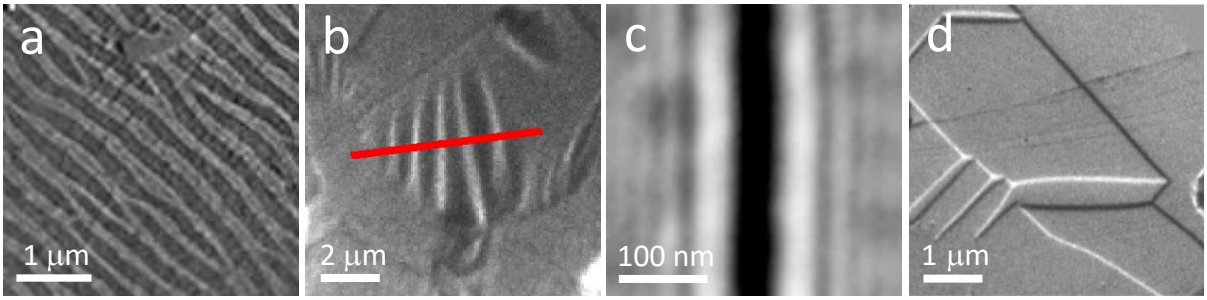


Fig 1. Experimental LEEM images obtained in defocus conditions of (a) a ridge-groove surface morphology of strained MnAs [7], (b) periodic ripples in freestanding graphene [5], (c) high-order atomic step fringes on Ag(111) [8], (d) small-angle facet boundaries on NiO(100) [9].

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P-017

High-Throughput UV-Laser-Based PEEM of Brain Tissue

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Large-scale connectomics aims to reconstruct neuronal circuits from serial brain sections. This requires imaging increasingly large brain volumes while maintaining the 10-nm-scale resolution required to identify synapses. Although multibeam scanning electron microscopy of serial sections represents the current state of the art, imaging throughput remains a major constraint on the volume that can be reconstructed within practical acquisition times.

Ultraviolet-laser-based PEEM offers an alternative route towards full-field, high-throughput imaging of mammalian brain sections. Our proof-of-concept studies demonstrated PEEM imaging of heavy-metal-stained ultrathin mouse brain slices, achieving 20 nm spatial resolution under Hg-lamp illumination and, under UV-pulsed laser illumination, millisecond exposure times and raw imaging throughputs approaching 10 GVox s^{-1} while retaining visible membrane contrast [1].

Extending these capabilities to higher imaging throughput without compromising spatial resolution requires careful optimization of the illumination conditions. To address this challenge, we integrated a CW UV laser source into an aberration corrected LEEM/PEEM instrument and developed an optical setup enabling rapid tuning of the laser spot size and power. By systematically varying these parameters, we identify operating conditions that minimize imaging exposure time and laser-induced damage while maintaining 10-nm-scale membrane contrast.

We present PEEM images of osmium-stained human brain tissue acquired under these optimized illumination conditions. These results demonstrate the feasibility of UV-laser-driven PEEM for short-exposure, synaptic-resolution imaging of brain tissue and highlight its potential for high-throughput connectomics.

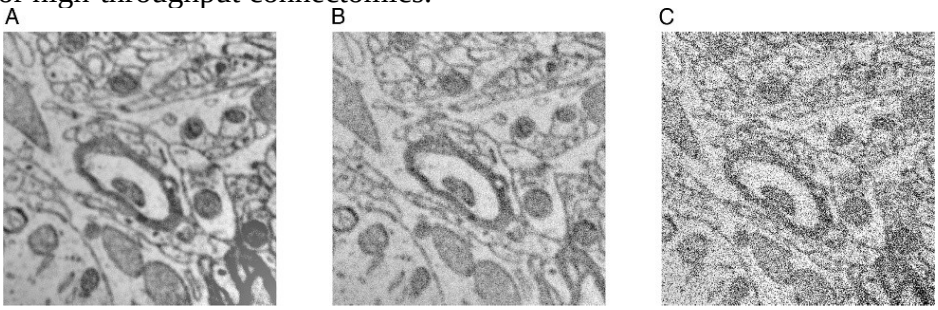


Fig 1. PEEM images of mouse brain tissue acquired under 266 nm CW laser illumination at raw imaging throughputs 0.1 (A), 1 (B), and 10 (C) GVox s^{-1}. Field of view: 6 µm. [1].

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P-018

LEEM/μLEED Study of Defect-Governed Low-Temperature Redox Transformations in Ar^+-Irradiated TiO_2 Surfaces

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Titanium dioxide (TiO_2) is a multifunctional material with a wide range of applications in catalysis, chemical sensing and nanoelectronic devices. Its technological relevance arises largely from the moderate chemical reactivity of its surfaces and their intrinsic ability to support and mediate ion-migration processes. Moreover, TiO_2 serves as a prototypical system for a broader family of transition-metal oxides, making it a valuable model material for studying defect-mediated surface chemistry, redox processes and electronic transport.

In this presentation, we report on the modification of rutile TiO_2 surfaces induced by low-energy Ar^+ ion irradiation. TiO_2(110) surface was irradiated with 2 keV Ar^+ ions at moderate fluences of up to 10^{17} ions/cm^2. The resulting structural and electronic changes were investigated using local-conductivity atomic force microscopy, in situ electron diffraction and microscopy techniques, including μLEED/LEEM, and X-ray photoelectron spectroscopy. The results show that ion irradiation produces a strongly reduced near-surface region extending over several tens of nanometres, accompanied by pronounced changes in local conductivity and surface ordering.

Particular attention is given to the thermal self-oxidation of Ar-sputtered TiO_2(110). Using operando X-ray photoelectron spectroscopy together with LEEM/μLEED analysis under UHV conditions, we demonstrate that redox processes in irradiated TiO_2 begin already well below 400 °C, significantly lower than commonly assumed for this material. Self-oxidation does not proceed through simple restoration of an ideal stoichiometric lattice but is instead governed by extended structural defects that are inherently present in real crystals and further activated by ion irradiation. These defects act as highly efficient pathways for oxygen migration, coupling ionic transport with electronic conduction and enabling a global insulator-metal transition under relatively mild annealing conditions.

The presented results show that LEEM/μLEED-based surface analysis, combined with local conductivity mapping and chemical spectroscopy, provides a powerful approach for following defect-mediated redox transformations in transition metal oxides. This makes Ar^+-irradiated TiO_2 a useful model system for understanding how extended defects control surface structure, oxygen exchange and electronic transport in functional oxide materials.

P-019

Concept and Aberration Analysis of a Flat-Electrode Mirror Corrector

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In electron microscopy, spatial resolution is fundamentally limited by optical aberrations. In particular, the lowest-order axial aberrations, namely third-order spherical aberration and second-rank chromatic aberration, are among the dominant factors that degrade image quality. Among various approaches to correct these aberrations, electron mirrors are widely used in electron optical systems, where spherical and chromatic aberrations can be compensated within a rotationally symmetric electrostatic configuration [1]. Such mirror-based systems offer a conceptually simple approach to aberration correction.

Conventional mirror correctors are typically composed of four electrodes, providing sufficient degrees of freedom to control focusing, spherical and chromatic aberrations, and field boundary conditions. In such configurations, the reflection field is formed primarily by the final mirror electrode, which generally requires a curved electrode surface to produce the desired concave equipotential distribution.

However, constructing mirror correctors based on curved electrodes involves several practical challenges, for example in accurately forming and maintaining the required electrode geometry.

Alternative configurations using planar electrodes have also been considered in previous studies [2], where the reflection field is primarily defined by the equipotential surface associated with a single planar mirror electrode. Although aberration correction can be achieved under certain conditions, such configurations lead to a restricted range of usable aperture angles.

To address this issue, we propose an alternative configuration in which the function of the mirror electrode is decomposed into multiple flat electrodes. In particular, a combination of a flat electrode and an aperture electrode is employed to generate an effective concave reflection field, thereby extending the conventional four-electrode mirror configuration to a five-electrode system.

Electron optical simulations were performed to evaluate the aberration characteristics of this configuration. The focusing condition was adjusted so that the object and image planes coincide, corresponding to unity magnification, and the aberration coefficients were calculated as functions of the electrode voltages. The results indicate that both spherical and chromatic aberration coefficients vary depending on the combination of electrode potentials, and their signs can be inverted under appropriate electrostatic conditions.

These findings suggest that the proposed concept provides a flexible approach to mirror-based aberration correction using only flat electrode geometries.

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P-020 Student

Characterizing a multi-pass transmission electron microscope

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Multi-pass transmission electron microscopy can improve the signal-to-noise ratio (SNR) for measurements limited by sample damage, beyond the capabilities of conventional single-pass measurement strategies. By utilizing the same electron pulse for *m* sequential interactions, the SNR can be improved by sqrt(*m*) [1,2]. We report the characterization of a 10 keV multi-pass transmission electron microscope. Consisting of a laser-triggered Schottky emitter, a magnetic prism, a knife-edge monochromator [3] and a re-imaging cavity with time-gated mirrors. Femtosecond and nanosecond electron pulses are emitted at MHz repetition rates with laser triggering. The photoemitted electron pulses are coupled into the main column, which hosts the re-imaging cavity that is made up of two time-gated mirrors [4] and ten lenses. The cavity is designed to form a unit magnification and chromatic and spherical aberration-corrected system [2,5]. Nanosecond gating pulses at the mirrors, which are synchronized to the MHz photoemission, allow coupling into and out of the re-imaging cavity. We provide an experimental analysis of the mirror's focusing and gating behavior. Additionally, we discuss spatially-resolved, single-shot electron counting capabilities with a YAG:Ce detector [6] at 10 keV, which requires low-aberration detection optics and very low-noise, high efficiency photon detection.

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P-021

Development of Femtosecond Photoemission Electron Microscopy at KEK

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This paper presents a femtosecond photoemission electron microscopy (fs-PEEM) system and shows some characteristic results. This system achieves a 100 fs temporal resolution and a 100 nm spatial resolution [1,2]. Additionally, continuously tuning the photon energy of the femtosecond laser from 0.5 to 6 eV yields an energy resolution of 30 meV (Fig. 1) [3,4]. Adjusting the photon energy to around the ionization energy of conduction band electrons suppresses core-level photoemission, thereby increasing the signal-to-noise ratio when detecting conduction electrons [3]. This approach enables the visualization of electron dynamics in operating organic field-effect transistors and inorganic diodes [5,6,7].

Furthermore, 100-attosecond-scale measurements are feasible using an interferometer (Fig. 2). Laser irradiation with an electric field period resonant with the period of a metal metastructure excites surface plasmons (free-electron density waves). These plasmons generate a localized electric field, triggering photoelectron emission. This configuration can serve as a high-efficiency electron source [8].

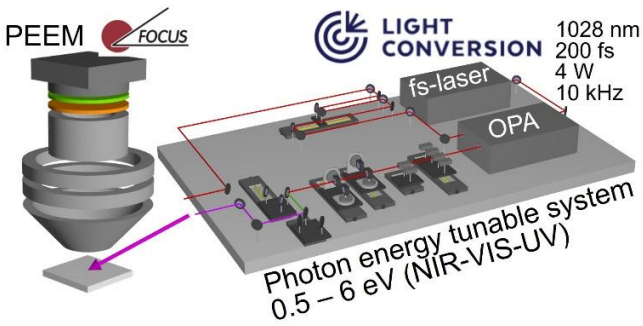


Fig. 1: PEEM with the photon energy tunable system.

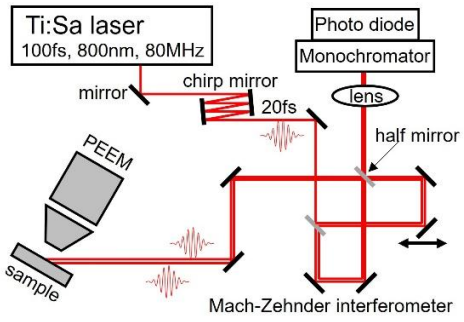


Fig. 2: Time-resolved PEEM system with an interferometer.

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P-022

Probing Switching Polarization in Ferroelectric Capacitors using laboratory based XPEEM

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The advent of CMOS compatible hafnia-based ferroelectrics has sparked intense interest in their use as ferroelectric capacitors (FeCAPs) in non-volatile memory cells. A compromise must be found between low operating voltage (for low power rating) and polarization switching (for maximum memory window), usually achieved at higher voltages.
In this work, we have studied the ferroelectric switching polarization as a function of the operating voltage via the shift in the Hf 4f binding energy and the work function of the top electrode.
The TiN(10 nm)/$Hf_{0.56}Zr_{0.44}O_2$(8nm)/TiN(10 nm)/W(50 nm)/Si(substrate) stack was made at NaMLab GmbH (Dresden) by ALD and post metallization annealing at 440°C for 240s and 400°C for 1h, both in N_2 atmosphere. The 40*40 μm^2 capacitors with 20 µm spacing were structured using standard lithography. The capacitors were then poled at ±1, ±2 and ±3V and imaged in PFM Fig.1 (left). The top electrode was thinned to 1.5nm using Ar ion beam sputtering at 500 eV in the ultra-high vacuum preparation chamber of the PEEM in order to access to the buried interface with the $HfZrO_2$ layer. The 180µm FoV PEEM threshold image of the capacitor field is shown in Fig.1 (center), allowing correlation between the work function and the poling voltage. Thanks to a recent acquisition of a high-power X-ray source (Thermo Scientific), we have performed Hf 4f core-level imaging of the capacitors in our laboratory PEEM (ScientaOmicron), Fig.1 (right). The binding energy of the Hf 4f core level provides the signature of the internal field due to the ferroelectric polarization.

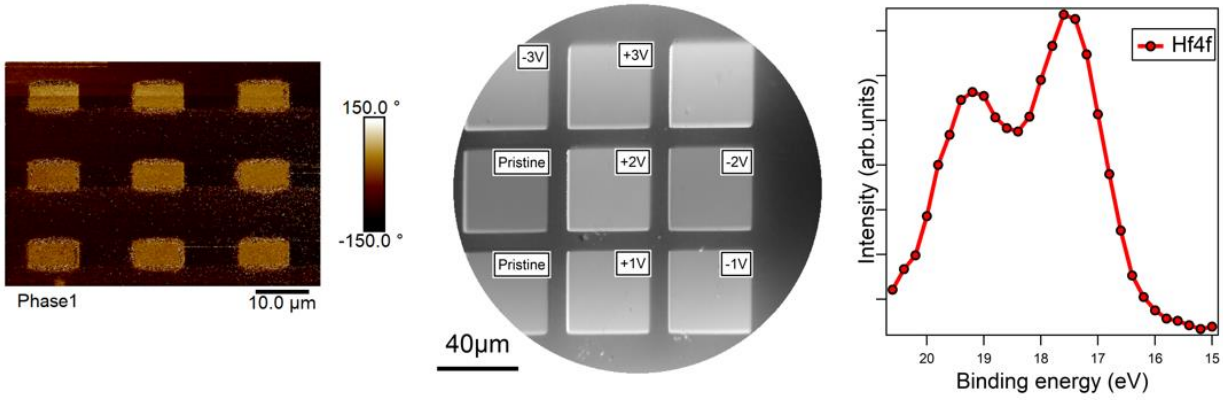


Fig 1. (left) PFM image of biased FeCaps. (center) PEEM threshold image of the capacitor field. (right) Spectrum of the Hf 4f core level

This work was supported by the European Union's Horizon Europe research and innovation program (Grant agreement No. 101135656) Ferro4EdgeAI.

P-023

Effect of electrode material on oxygen vacancy concentration and evolution with field cycling in ultra-thin, ferroelectric $Hf_{0.5}Zr_{0.5}O_2$-based capacitors

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Hafnia-based, ferroelectric capacitors (FeCAPs) can enable advanced node integration of non-volatile, random-access memories thanks to their scalability, and full compatibility with complementary-metal-oxide-semiconductor technology. Oxygen vacancies (V_O) play a crucial role in FeCAP performance, including wake-up, imprint and endurance. We have carried out a comparative study of the influence of TiN and W electrodes on the V_O concentration profile as a function of polarization state in pristine, woken up and fatigued conditions of ultrathin $Hf_{0.5}Zr_{0.5}O_2$ FeCAPs.

The top electrode was thinned to < 2 nm so that the probing depth of the Hf 4f emission was sensitive to the interface region in the $Hf_{0.5}Zr_{0.5}O_2$. Capacitors were identified using LEEM. Spatially resolved, X-ray Photoemission Electron Microscopy (XPEEM) using synchrotron radiation at MAX-IV synchrotron (Lund, Sweden) was employed to characterize 20×40 μm^2 sized structures, chosen to minimize leakage currents. Assuming doubly positively charged vacancies, the Vo concentration can be directly linked to the reduced fraction of the adjacent metal ions, specifically the Hf^{3+} component of the Hf 4f spectrum. For TiN electrodes we observe V_O accumulation (depletion) near the top interface in downwards (upwards) polarization states consistent with drift under the internal polarization field whereas with W electrode no significant V_O concentration is recorded, whatever the cycling state. These in-situ experiments demonstrate the oxygen scavenging by TiN which may influence both endurance and imprint.

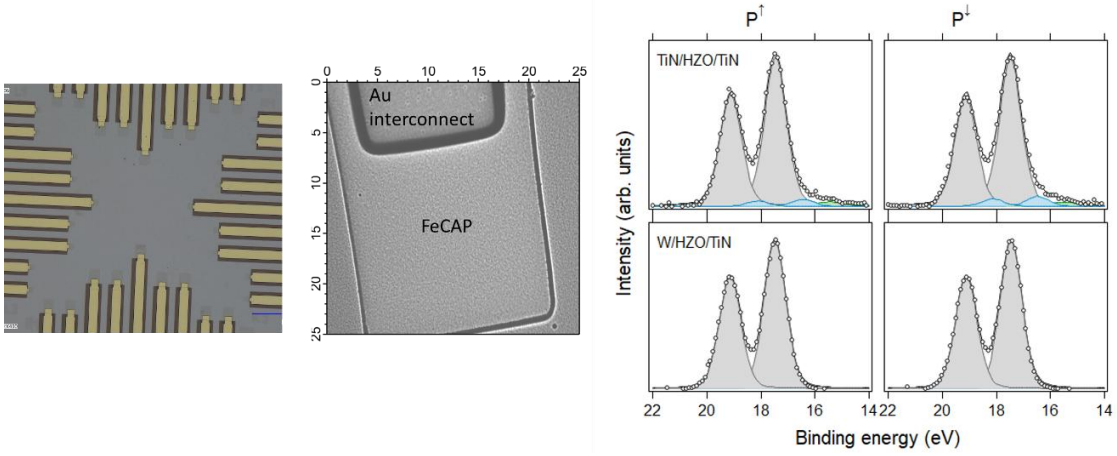


Fig 1. (left) Optical micrograph of FeCAP layout and LEEM image of a 20×40 μm^2 FeCAP. (right) Hf 4f XPEEM from individual FeCAPs with TiN and W electrodes in $P^{\downarrow}$ and $P^{\uparrow}$ after wake-up.

This work was supported by the Agence Nationale de Recherche (ANR) and Deutsche Forschungsgemeinschaft (DFG) within the project D3PO.

Visualization of Latent Electron-Beam Lithography Patterns Using Photoemission Electron Microscopy

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In lithography processes, pre-development observation of light- or electron-beam (EB) exposed patterns (latent images) is challenging because the physical changes in the resist after exposure are too subtle to be detected by conventional microscopy techniques such as optical microscopy or scanning electron microscopy. Nevertheless, photoemission electron microscopy (PEEM) is a promising technique for this purpose, as it can visualize latent images as chemical contrast with high throughput [1].

In this study, we observed line patterns fabricated on a positive-tone EB resist (ZEP520A) using PEEM. After spin-coating ZEP520A onto an ITO substrate, line patterns with widths ranging from 2 μm to 10 nm were exposed by EB lithography. The patterns were subsequently examined using PEEM with a 266 nm femtosecond pulsed laser. Clear contrast was observed as bright lines for feature sizes from 2 μm down to 100 nm. However, for line widths below 100 nm, visual distinction became difficult due to background contrast originating from the resist. To address this limitation, Fast Fourier Transform (FFT) analysis was performed using ImageJ. This approach enabled separation of the periodic line patterns from the resist-derived background based on their spatial frequency components. As a result, we successfully identified latent images with line widths below 100 nm, demonstrating the capability of PEEM for nanoscale latent image detection. Furthermore, energy-filtered PEEM measurements were conducted, and energy distribution curves were extracted from both exposed and unexposed regions to investigate the origin of the latent-image contrast.

In future work, we plan to extend this approach to other resist systems, such as PMMA, to evaluate the general applicability of PEEM for latent image observation.

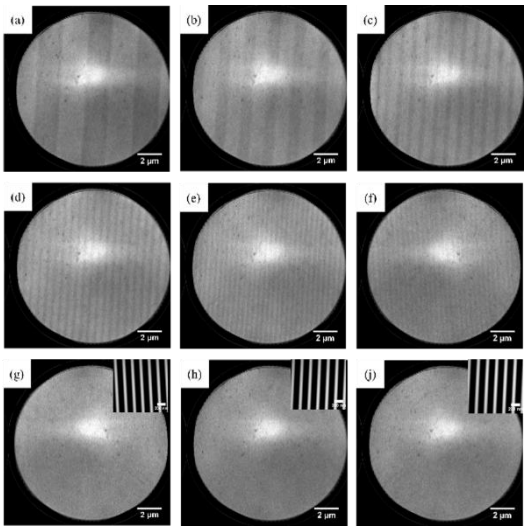


Fig 1. Latent images of different width line patterns. The line patterns with line widths of (a) 2 μm, (b) 1 μm, (c) 500 nm, (d) 300 nm, (e) 200 nm, (f) 100 nm, (g) 50 nm, (h) 30 nm, (i) 10 nm. The inserted images in (g), (h), and (i) are inverse-FFT images of the spatial-frequency components detected from the line patterns.

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P-025 Student

Imaging Polarization-Dependent Excited-State Photoemission Matrix Elements in SnSe

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SnSe is a layered thermoelectric semiconductor with pronounced in-plane anisotropy in its electronic structure, optical response, and carrier dynamics. In this work, we investigate how excited-state photoemission matrix elements shape the momentum-resolved photoemission response of bulk SnSe using time- and polarization-resolved momentum microscopy. Near-infrared pump pulses are used to transiently populate multiple conduction-band electron pockets, which are subsequently photoemitted and imaged by ultraviolet probe pulses with controlled linear polarization. We find that the symmetry and intensity distribution of the photoelectron angular distribution (PEAD) depend sensitively on the orientation of the probe polarization relative to the crystallographic axes. By rotating the probe polarization and varying the incidence geometry, we distinguish intrinsic electronic anisotropy from photoemission matrix-element effects associated with the probe field. The observed polarization-dependent PEAD patterns reveal that excited-state photoemission from SnSe is governed not only by the transient conduction-band population, but also by the symmetry-selective coupling between the initial states, final states, and optical excitation geometry. These results highlight momentum microscopy as a powerful approach for disentangling excited-state dynamics and photoemission selection rules in anisotropic quantum materials.

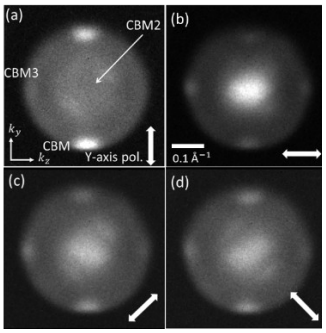


Fig 1. Polarization-dependent PEAD images of SnSe. (a–d) PEAD patterns acquired at normal incidence under different incident light polarizations. The pronounced redistribution of photoemission intensity reveals the polarization-dependent excited-state response of SnSe.

P-026

PEEM and LEEM visualization of the anode surface growth in anode-free solid-state batteries: influence of metal interlayer

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A detailed understanding of the mechanisms involved in the surface growth of metals has been a fundamental branch of Surface Science, not only from a basic scientific interest but also from a technological point of view to improve real devices. An example of the last type is the study of the anode formation in solid state (Li, Na) batteries where the anode growth mode will have a strong influence on the subsequent discharge/charge cycles: uncontrolled growth can produce capacity losses or battery failure (because "dead" layers or stress concentrations producing growth of dendritic structures). In this work we use LEEM and PEEM to study the anode growth modification due to the addition of interlayers in solid-state anode free batteries: these battery types are composed of a cathode that supplies the alkali metal, a solid electrolyte that is usually a ceramic (or polymeric) material, and a metallic current collector layer on top. The anode is formed in situ at the interface of the electrolyte and the current collector during the first charging cycle of the battery. Surface science experimental conditions (cleanliness, UHV, surface sensitivity…) are far from the real battery environment, so special experimental design must be done to replicate working conditions: in order to visualize with LEEM and PEEM the anode growth at the electrolyte surface during the battery charging we have removed the current collector layer and used the electron gun of the LEEM microscope to charge electrically the electrolyte surface thus promoting the Li/Na diffusion from the cathode through the electrolyte to the surface [1].

It is known that in heteroepitaxial growth of metals and semiconductors the influence of overlayers of some materials or surfactants can induce modifications in the growth mode. In a similar strategy we have grown overlayers of two different materials ("interlayers") on the electrolyte to modify the anode growth: depending on the material (Ag, Mg) and thickness of the interlayer we have observed different regimes, from changes in island size/density to growth partial suppression. We have used synchrotron spectromicroscopy (XAS-, XPS-XPEEM) to study the chemistry of the anode nucleation and the different chemical species present at the interface.

Reference

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P-027

Current development status of the PEEM station at BL09 of NewSUBARU synchrotron

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NewSUBARU is a medium-sized synchrotron radiation facility located on the SPring-8 campus, administered and operated by the University of Hyogo (Fig. 1 (a)). By utilizing the radiation from extreme ultraviolet (EUV) to soft X-ray regions, it has served as a foundational platform for EUV lithography development. In 2021, a PEEM apparatus (FOCUS GmbH) was installed at the long undulator beamline BL09, specifically for the nanoscale spectroscopic analysis of EUV resist materials. To meet diverse industrial analytical demands, e.g., catalysts, batteries, and hydrogen-strategy materials, we have recently modified the instrument to enhance its versatility.

The photograph of upgraded PEEM apparatus is shown in Fig. 1 (b). The specific modifications include three major improvements. First, the conventional integrated stage (IS) was replaced with a manipulator system, enabling the apparatus to accommodate various sample shapes brought in by external users. Second, by repositioning the PEEM station at the beamline's focal point (by removing the old apparatus), the incident beam flux density was successfully enhanced. Third, the entire lens system was rearranged into a vertical configuration to effectively utilize the aspect ratio of the horizontally elongated beam.

Figure 1 (c) presents a PEEM image and region-selected X-ray absorption spectra (XAS) from a mixed surface of graphite (HOPG) and carbon tape. The NewSUBARU light source exerts good performance in XAS analysis at the K-edges of light elements such as C, N, and O, the region where large facilities like SPring-8 suffer from contamination of optical instruments. The upgraded PEEM station at NewSUBARU is expected to play a complementary role to major synchrotron facilities in various industrial applications, particularly for soft materials analysis.

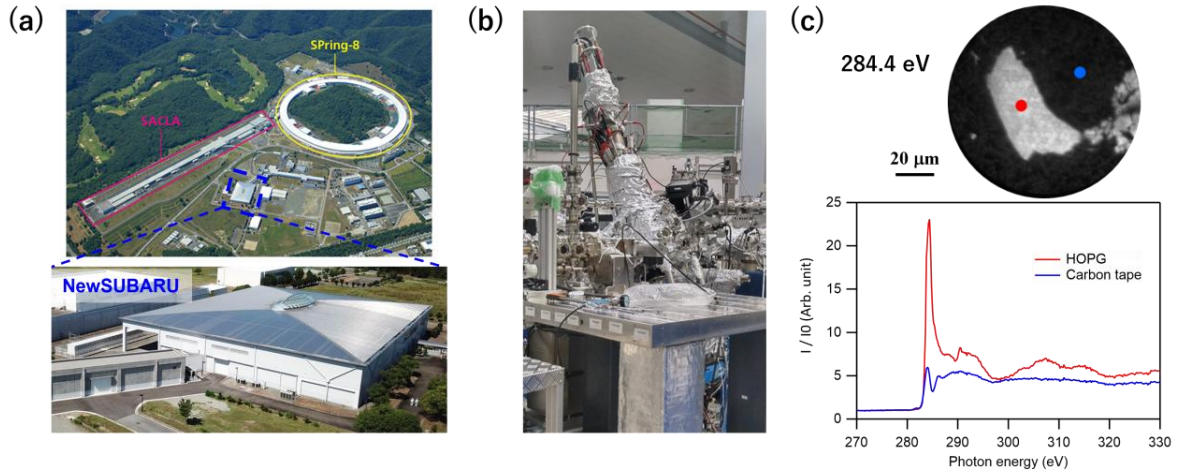


Fig 1. (a) Location of New SUBARU synchrotron. (b) Photograph of PEEM apparatus at BL09. (c) X-PEEM image and area-selected XAS spectra of HOPG and carbon-tape mixed surface.

Multi-wavelength laser photoelectron electron microscopy

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The choice of excitation photon energy plays an important role in photoemission electron microscopy (PEEM) characterizations, as it determines the accessible photoemission range for different materials. Here we developed a multi-wavelength laser source for PEEM, providing multiple selectable wavelengths of 266 nm, 177 nm, and 225-230 nm, corresponding to photon energies of 4.66 eV, 7.00 eV, and 5.39-5.51 eV, respectively. These excitation energies expand the accessible photoemission window and enable flexible characterization of materials with different work functions and surface electronic properties. Importantly, a flat lens with a long focal length was employed to achieve a micrometer-sized laser spot in vacuum for high-resolution PEEM imaging. Based on the optical design, all the wavelengths have been successfully integrated into cryogenic PEEM experiments, demonstrating the practical applicability of the laser system for surface-sensitive imaging and electronic-structure analysis. This multi-wavelength laser source offers a versatile optical excitation solution for PEEM studies of material surfaces and interfaces.

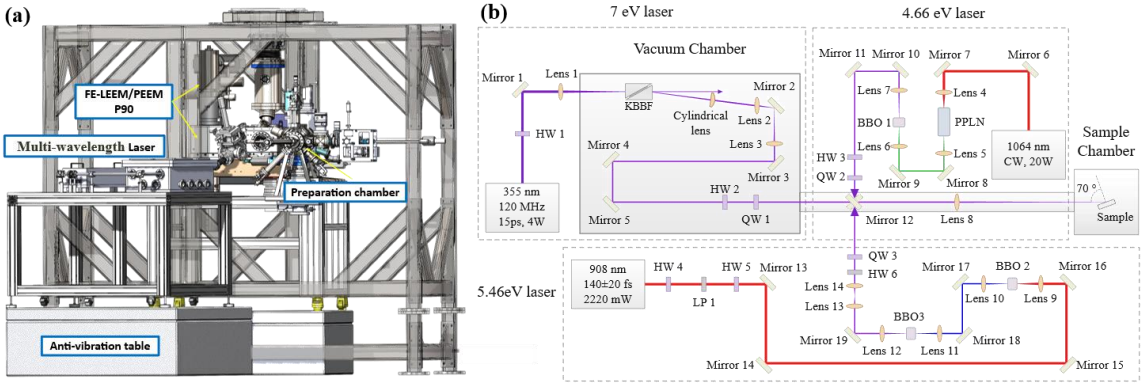


Fig 1. (a) Schematic of the LEEM/PEEM system equipped with a self-developed multi-wavelength laser source; (b) Optical layout of the multi-wavelength laser system, which provides wavelengths of 266, 227, and 177 nm.

Reference(s)

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P-029

Interplay Between Structure and Interfacial Interactions in Fe-Gd Synthetic Ferrimagnets

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Transition metal–rare earth ferrimagnets are attractive model systems for next-generation spintronic devices, where magnetic domain configurations and their thermal evolution determine functionality. In this talk we investigate ultrathin Fe–Gd ferrimagnetic heterostructures grown epitaxially on W(110) by atomic layer deposition using element-selective XMCD-PEEM complemented by structural characterization [1]. By comparing Gd/Fe and Fe/Gd bilayers with compositionally homogeneous Fe(1−x)Gdx alloys, we demonstrate that both the Curie temperature and the magnetic domain behavior are primarily controlled by crystallinity and interfacial exchange coupling. In crystalline Gd/Fe bilayers, the Gd layer remains ferromagnetically ordered up to ~500 K, far above the Curie temperature of bulk Gd, owing to strong interfacial coupling to Fe. In contrast, the reduced crystallinity of the Fe layer in Fe/Gd suppresses the Fe magnetic order, leading to a common Curie temperature of ~325 K, comparable to that of the homogeneous alloy (~345 K). Atomistic spin simulations reproduce the experimental observations and reveal the crucial role of structural disorder in determining the magnetic response. These results demonstrate that interface engineering provides an effective route to tailor Curie and compensation temperatures in ultrathin ferrimagnetic heterostructures, opening new opportunities for thermally robust and energy-efficient spintronic devices.

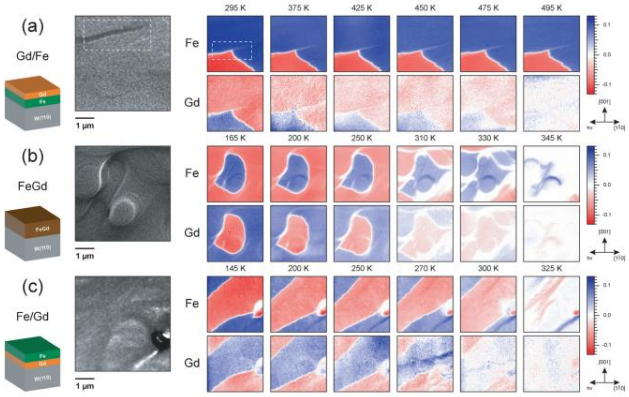


Fig 1. LEEM and XMCD images taken at the Fe L3 and Gd M5 absorption edges maxima at selected temperatures for (a) Gd/Fe bilayer (3.7 ML Gd, 6.0 ML Fe), (b) FeGd alloy and (c) Fe/Gd bilayer (6.2 ML Fe, 3.6 ML Gd) [1].

Reference(s)

[1] Álvaro González-García1 Alejandro Álvarez-Chico Jairo Obando-Guevara Silvia Gallego Unai Atxitia Iulia Cojocariu Matteo Jugovac Tevfik Onur Menteş Andrea Locatelli Arantzazu Mascaraque Miguel Ángel González-Barrio, *Advanced Electronic Materials*, **0e00686**, (2026).

P-030 Student

Spatiotemporal Imaging of plasmon-dressed Exciton-Polaritons in CrSBr

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Ultrafast imaging of polaritonic fields is essential for understanding directional energy transport in anisotropic quantum materials. Here, we use gold circular-ring nanostructures as plasmonic near-field sources to launch exciton polaritons in van der Waals antiferomagnetic CrSBr, and probe the polaritonic propagtion using interferometric time-resolved photoemission electron microscopy to probe ultrafast exciton-polariton dynamics in the magnetic van der Waals semiconductor CrSBr [1,2]. The localized surface-plasmon-polariton near fields couple to the strong anisotropic exciton resonance of CrSBr, enabling near-field excitation and detection of polaritonic modes governed by its in-plane optical anisotropy. Power-dependent PEEM measurements show a fourth-order nonlinear scaling of the photoemission yield, indicating that the detected near-field contrast is dominated by a four-photon photoemission process. By varying the excitation wavelength, we map the exciton-polariton dispersion and observe an avoided crossing near the CrSBr exciton resonance, providing evidence for the formation of coupled plasmon–exciton polaritons [3]. Interferometric time-resolved measurements further resolve the real-space propagation of these modes and reveal pronounced direction-dependent transport consistent with the anisotropic polariton dispersion [2]. These results connect the spectral signature of plasmon–exciton coupling with ultrafast spatiotemporal polariton dynamics, and provide a promising route toward on demand polariton engineering in low dimensional materials. polariton motion.

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Meso-scale structural evolution and phase transitions of dicarboxylic acids on metal surfaces

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Molecular self-assembly of small dicarboxylic acids on metal surfaces provides a prototypical system for studying surface-induced chirality [1]. While the resulting molecular phases have been extensively characterized by static techniques, the dynamic pathways of their thermal evolution and the real-time observation of chiral amplification in mixed layers remain unexplored.

Here, we use in-situ low-energy electron microscopy (LEEM) and low-energy electron diffraction (LEED) to directly monitor the structural evolution of succinic acid (SU) and tartaric acid (TA) adlayers on Cu(110). Distinct changes in the diffraction pattern are observed during thermal cycling, indicating successive structural transformations of the molecular layer (Fig. 1). Real-time LEEM imaging further reveals the evolution of molecular domains and their spatial distribution across the surface.

The methodology is further applied to co-adsorbed SU–TA monolayers to investigate chiral amplification through the sergeants-and-soldiers principle, where small amounts of chiral TA direct the organization of achiral SU. This provides a well-defined platform for exploring the real-time emergence of chirality in mixed molecular layers during thermal annealing.

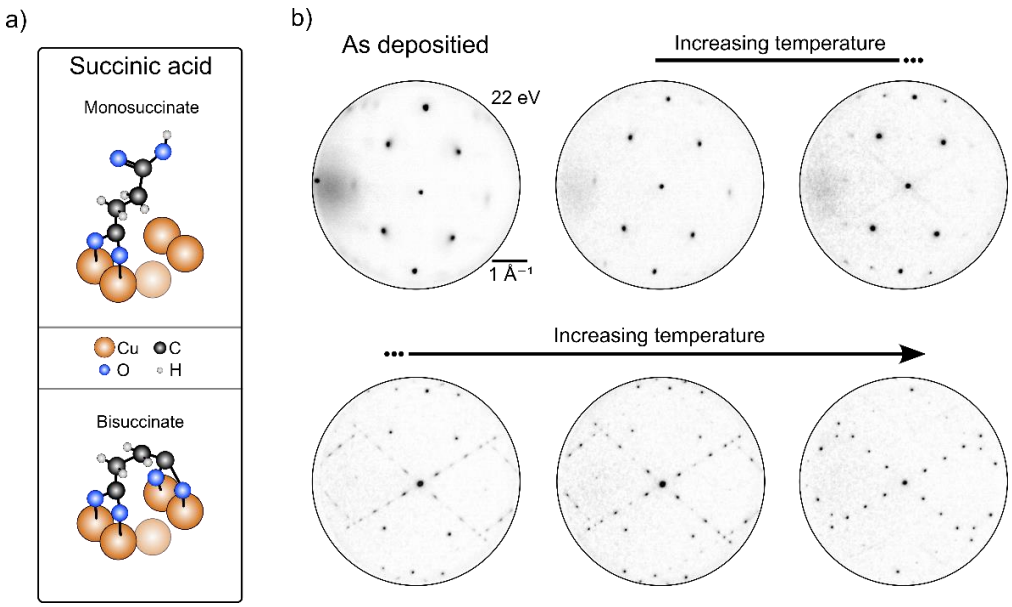


Fig 1. a) Molecular model of succinic acid in two adsorption modes; monosuccinate and bisuccinate. b) Microdiffraction pattern of SU molecules on Cu(110) acquired during annealing.

Reference(s)

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P-032

Electron microscopy at work: HREELS development in LEEM and TEM characterization of BDPA encapsulated in BNNTs

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The first part focuses on the impact of design criteria guiding the implementation of spherical electron energy filters onto an aberration-corrected LEEM (AC-LEEM) instrument. It was found [1] that a symmetrical configuration of a tandem of Hemispherical Deflector Analyzers (HDAs) allows a natural dispersion-compensation of aberrations, which can significantly improve the performance of the LEEM instrument in terms of energy resolution. Thus, implementing HDAs onto an AC-LEEM (Fig. 1A) would allow HREELS capabilities within the LEEM instrument. The voltages applied to the LEEM components and the HDAs impose additional electrostatic accelerating/decelerating transfer lenses (TL) placed at the entrances and exits of the HDAs. We will present the final design of TLs that were simulated in conditions of decelerating and accelerating electron beam between 15 and 0.1 keV.

The second part focuses on the encapsulation of BDPA free radicals (1,3-bisdiphenylene-2-phenylallyl, also known as Koelsch's radical) into Boron-Nitride Nanotubes (BNNTs) and their characterization using Transmission Electron Microscopy (TEM). BDPA is a persistent radical at normal temperature and pressure. Koelsch's radical is paramagnetic due to its carbon centered unpaired spin *S=1/2* and in crystalline regime, it behaves as an antiferromagnet. Interestingly, a ferromagnetic behavior of BDPA is observed once it is encapsulated and it could be due to its confinement and aggregation in the BNNTs which can be studied by TEM. The encapsulation of BDPA@BNNTs were confirmed using Energy-Filtered TEM (EFTEM) (Fig. 1B).

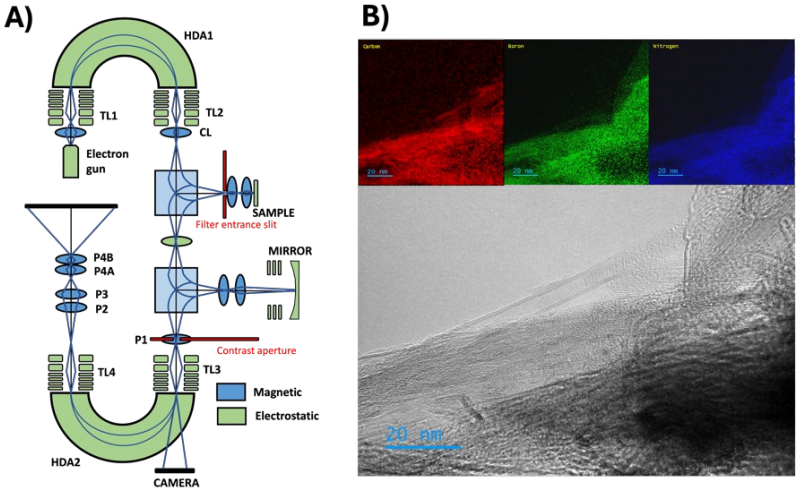


Fig 1. Scheme of the HREELS–LEEM system proposed with the HDAs positioned between the electron gun and the condenser lens and between the first and second projector lenses (A). TEM brightfield image with EFTEM images of BDPA@BNNTs (B).

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P-033

Using Momentum Microscopy as a Screening Tool for Many-Body Interactions in Electronic Band Structures

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State-of-the-art momentum-resolved photoemission electron microscopes (*k*-PEEMs) can access large regions of the momentum space from µm-scale surface areas, at fixed light-to-sample geometries and with sub-20-meV and sub-0.01 Å^{-1} resolutions [1]. Despite this, using *k*-PEEM to resolve fine structure in electronic band dispersions, such as many-body interaction signatures, has remained largely underappreciated.

We argue that *k*-PEEM constitutes an efficient and accessible screening tool for many-body-derived energy renormalizations, capable of guiding targeted, higher-resolution synchrotron ARPES studies. Previously, *k*-PEEM surveys have uncovered both charge transfer and interlayer confinement effects [2,3]. Herein, we will explicitly demonstrate how its use can be extended to the many-body physics regime, exemplifying our workflow through two laboratory-source studies [4,5]: electron-phonon coupling signatures in the π-band of exfoliated hexagonal boron nitride (hBN); and phonon- and magnon-coupling to the spin-split surface resonance electrons of Ni(111). In both cases, *k*-PEEM is used to identify the relevant renormalization signatures, and then subsequently confirmed and quantified using µm-scale, synchrotron ARPES (see Fig. 1). Given the growing availability of laboratory-based momentum microscopes, our two-step approach offers an accessible and high-throughput route to uncover overlooked many-body physics in systems where spatial selectivity is essential.

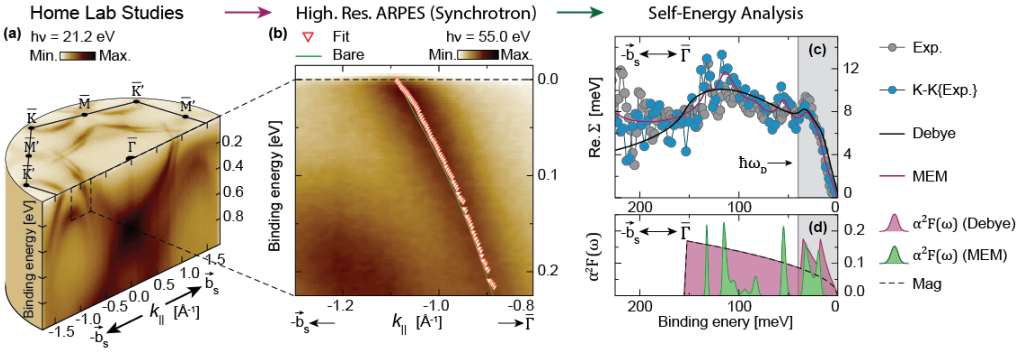


Fig 1. Many-body physics discovery from Ni(111). (**a**) *k*-PEEM screening → (**b**) synchrotron ARPES → (**c**) self-energy quantification and disentanglement of electron-boson couplings.

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P-034 Student

Momentum Microscopy Study of Coexisting Spin-Polarized Metallic Surface State and Si-Derived Two-Dimensional Electron Gas in Bi/Si(111)-β

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Bi/Si(111)-β is known to host semiconducting surface states with giant Rashba splitting due to strong spin–orbit interaction and broken surface inversion symmetry [1]. Since dispersive surface states can determine the Fermi-level position at metal/semiconductor interfaces [2], understanding the electronic structure of Bi/Si(111)-β is essential for clarifying its interfacial band alignment.

We investigated Bi/Si(111)-β using photoelectron momentum microscopy with a 10.9 eV vacuum-ultraviolet laser [3]. One monolayer of Bi was deposited on clean Si(111) 7×7 at approximately 300 °C and subsequently annealed. STM and LEED-IV measurements showed that highly crystalline β-phase samples were obtained after annealing near 450 °C.

Full momentum-space mapping revealed a previously unreported Bi-derived metallic surface state crossing the Fermi level near Γ, whose spin polarization was suggested by spin-resolved measurements. We also observed small electron pockets likely derived from the Si conduction band, indicating the formation of a Si-derived two-dimensional electron gas near the interface. The larger Fermi surface of the Bi-derived state suggests that it dominates the interfacial charge balance. We discuss the band alignment at the Bi/Si(111)-β interface based on these results.

References

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P-035

Simulation of PEEM images

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Photoemission Electron Microscopy (PEEM) is a powerful characterization technique that enables the simultaneous acquisition of surface topography and material properties, such as the work function, with nanometer-scale spatial resolution. However, in order to quantitatively relate the contrast in PEEM images—namely, differences in signal intensity—to the underlying physical properties of interest, appropriate data conversion or computational analysis is required. For instance, it has been reported that surface topographical features, such as steps, can generate contrast through the deflection of electron trajectories [1]. In practical samples, image contrast generally arises from multiple contributing factors, which makes its interpretation nontrivial.

Numerical simulation is therefore an effective approach for disentangling and interpreting PEEM image contrast. In this study, we developed a simulation algorithm for PEEM imaging. In this presentation, we describe the details of the proposed algorithm, demonstrate its application to periodic grating-like surface topographies with varying feature dimensions, and compare the simulation results with experimentally obtained PEEM images.

Reference

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P-036 Student

Detection of Orbital Angular Momentum in Chiral Tellurium by Circular Dichroism Angle-Resolved Photoemission Spectroscopy

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Chiral materials, which lack both inversion and mirror symmetries, possess enantiomeric crystal structures and exhibit various physical properties derived from their chirality. Recent theoretical perspectives have highlighted that structural chirality can lead to electronic chirality via orbital degrees of freedom, manifesting as orbital-angular-momentum (OAM) textures [1]. This orbital-momentum locking is predicted not only to induce orbital splitting but also to play a fundamental role in emerging phenomena such as orbital Hall effect [2] and Chirality-Induced Spin Selectivity (CISS) [3]. Specifically, it has been predicted that in elemental tellurium, a prototypical chiral material consisting of helical chains along *c*-axis, the OAM drives the huge breaking of degeneracy in the momentum-dependent electron band dispersions, and realizes the electronic chirality [1]. However, direct spectroscopic observations of OAM textures remain limited to materials such as B20-type crystals [4].

In this work, we performed circular dichroism angle-resolved photoemission spectroscopy (CD-ARPES) on bulk Te single crystals to detect the OAM texture and orbital splitting in momentum space. The experiments were conducted with the light incidence plane aligned parallel to the helical atomic chain direction (*c*-axis), to probe L_z *i.e.* the OAM component along *c* axis. To clarify the correspondence between the structural chirality and the electronic states, we performed systematic measurements on both enantiomers and the CD-ARPES results reveal the sign reversal depending on the structural chirality of Te. We further analyzed the difference between the CD-ARPES signals obtained from these two enantiomers and eliminated extrinsic contributions arising from the experimental geometry. Based on these results, we discuss the extracted chirality-dependent CD-ARPES in relation to the OAM textures predicted by theory.

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P-037

Simulation of PEEM and LEEM measurements of complex sub-micron structure and topography

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Low Energy Electron Microscopy and PhotoEmission Electron Microscopy are both powerful techniques which allow to image multiples surface inhomogeneity with high throughput. The imaging contrasts due to the deviation of electrons by electric field inhomogeneities, as a consequence of topography or work function inhomogeneity, is well understood and modeled in simple geometry. However, intricate sub-micron tridimensional structure, as common in modern electronics, can make the interpretation of PEEM and LEEM contrasts difficult.

The presented work developed software in order to address the simulation of PEEM and LEEM measurements of complex sub-micron structure. We report about the simulation of the contrast due to the deviation of electrons in complex sub-micron structure and we compare our results with measurements.

The presented results bring further understanding and modeling of the PEEM and LEEM contrasts in complex sub-micron structure, as pursued for potential application.

P-038 Student

Visualization of Topological Edge Modes Using Femtosecond Time-resolved PEEM

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A structure in which prism-shaped gold (Au) nanostructures are arranged in a triangular lattice serves as a plasmonic crystal (PlC). At the boundaries where these patterns are inverted and face each other, a new state, a topological edge mode, emerges within the energy band gap [1,2].

To observe the spatiotemporal dynamics of both the edge and bulk modes excited in the PlC, we performed time-resolved photoelectron emission microscopy (PEEM) using a 20-fs pulsed laser. The laser pulse was shaped into a pulse pair with a time delay τ using a Mach–Zehnder interferometer. The spatial distribution of photoelectron intensity was recorded as PEEM images while sweeping the delay time τ with attosecond precision. Fig. 1(a) shows a representative PEEM image and a scanning electron microscopy (SEM) image of the PlC. The PEEM image reveals pronounced photoelectron enhancement in the edge region in addition to the bulk. Fig. 1(b) shows the τ dependent photoelectron intensity in the bulk and edge regions. For τ = −20 to 20 fs, the oscillations in the bulk and at the edge coincide. However, for |τ| > 20 fs, the phase begins to shift. The phase advance in the edge region suggests a higher oscillation frequency while retaining a coherence lifetime comparable to the pulse duration. The delay dependence of the oscillation phase and amplitude is well described by a Lorentz oscillator model.

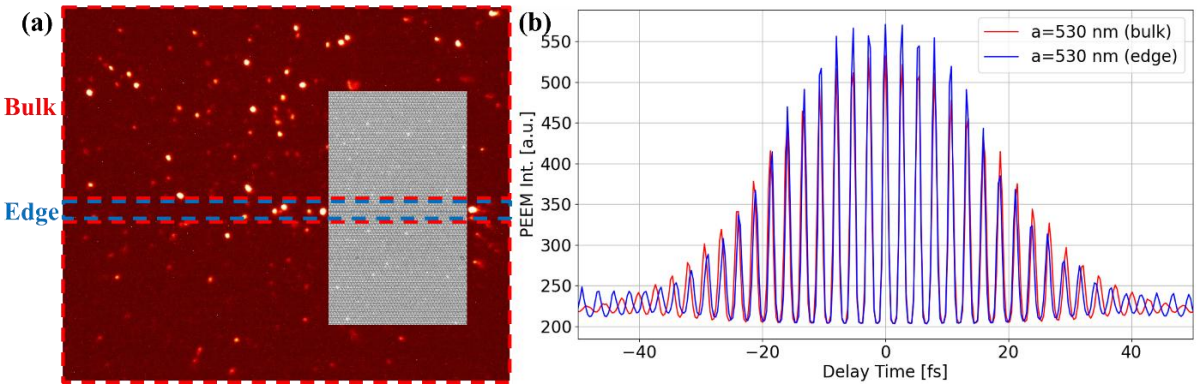


Fig 1. (a) A PEEM image (τ = −21.2 fs) and a SEM image of PlC.
(b) Averaged PEEM intensities at bulk and edge regions as a function of delay time τ.

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P-039

XAS-PEEM Imaging and Spectroscopy of Liquid Water Using a SiN_x Membrane Liquid Cell

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Direct observation of liquid samples at the mesoscopic scale (5–100 nm), where biological and chemical structures overlap, is highly significant for battery research, biotechnology, and photocatalysis. We aim to realize operando observation of liquid-phase phenomena by exploiting the spatial resolution and chemical-state sensitivity of X-ray absorption spectroscopy-photoemission electron microscopy (XAS-PEEM). We developed a liquid cell for XAS-PEEM using a TEM window chip with a free-standing SiN_x membrane. The SiN_x membrane window was 25 × 25 μm² in size and 5 nm thick (Fig. 1(a)). Pure water was introduced into the well beneath the membrane, and soft X-rays were irradiated onto the water through the SiN_x membrane (Fig. 1(b)). We used a PEEM system manufactured by FOCUS GmbH at beamline BL09A of the NewSUBARU synchrotron radiation facility, University of Hyogo. The system enables element-selective XAS-PEEM observation by tuning the photon energy of soft X-rays generated by an undulator. PEEM images were acquired at 537.5 eV, corresponding to the water resonance, and at 525 eV, off resonance [1, 2]. By subtracting these images, the distribution of water beneath the SiN_x membrane was clearly visualized (Fig. 1(c)). These results demonstrate XAS-PEEM imaging and spectroscopy of liquid water using the developed liquid cell.

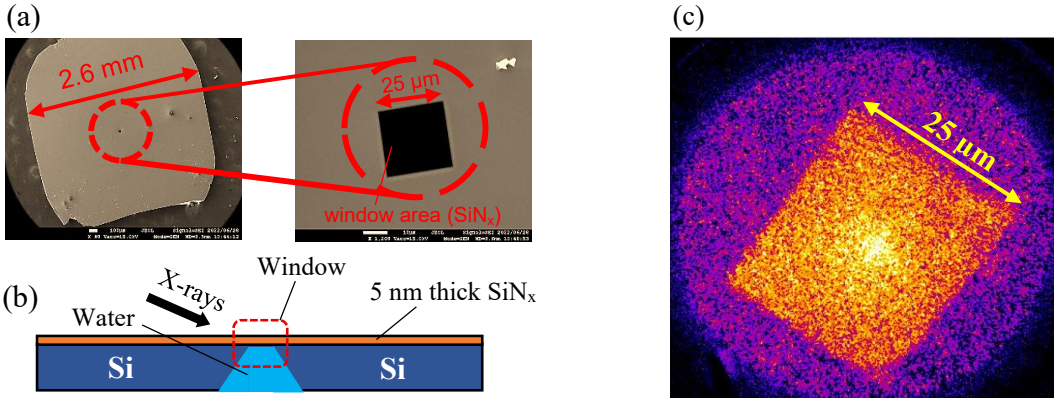


Fig. 1. (a) SEM images of the TEM window chip. (b) Schematic of the liquid cell. (c) Subtraction image of PEEM images acquired at incident photon energies of 537.5 and 525 eV.

Acknowledgement
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Development of Multidimensional Photoemission Electrons Microscopy (PEEM)

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We develop a multidimensional time-resolved photoemission electron microscopy platform for probing non-equilibrium quantum matter across real space, time, energy, and momentum. The instrument integrates energy-filtered PEEM imaging, local photoelectron spectroscopy, momentum microscopy, dual-color pump–probe delay scanning, and interferometric phase scanning within a single apparatus. In interferometric NIR operation across the 1.2–1.9 eV range, the platform provides sub-20-fs temporal resolution with phase precision approaching 100 as, while NIR–UV pump–probe measurements achieve a time resolution of ~50 fs. Depending on the operation mode, the joint space–time–energy–momentum resolutions reach approximately 10 nm, 10–50 fs, 50–100 meV, and 0.05 Å^{-1}. This platform enables direct visualization of ultrafast optical near fields, transient band shifts, nanoscale photovoltage landscapes, domain-dependent dynamics, and momentum-selective photoemission channels, offering a versatile route to resolve and control light-driven microscopic processes at their intrinsic nanometer–femtosecond scales.

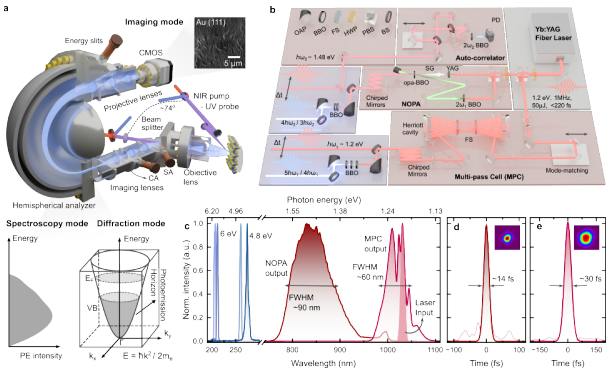


Fig 1. Instrument overview of NIR-UV frequency-tunable time-resolved photoemission electron microscopy (PEEM).

P-041

Chiral Antiferromagnetic domain walls on exchange coupled $La_{1-x}Sr_xMnO_3/LaFeO_3$//STO(001) bilayers

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Exchange-coupled heterostructures of magnetic perovskites provide an ideal platform to study mutual interactions across ferromagnetic–antiferromagnetic (FM–AF) interfaces[1], as their magnetic properties are extremely sensitive to strain and composition. We show that the combination of spin-flop exchange coupling across La_{1-x} $Sr_xMnO_3/LaFeO_3$ interfaces grown on STO(001), together with the canted Néel-axis orientations of antiferromagnetic $LaFeO_3$, can induce chirality in the AF domain walls.

By combining X-ray Magnetic Linear Dichroism (XMLD) and X-ray Magnetic Circular Dichroism (XMCD) PEEM imaging, we find that strong exchange coupling fully transfers the AF domain pattern into the FM top layer. Through a detailed pixel-resolved analysis of the angular XMLD and XMCD dependencies, we extract the complete Néel and magnetization vectors across the FM–AF domain walls. We reveal a direct correspondence between FM vortex cores in the LSMO layer and chirality reversals of the AF LFO domain walls. These findings open new avenues for understanding the interplay between exchange and magnetoelastic interactions at FM–AF interfaces.

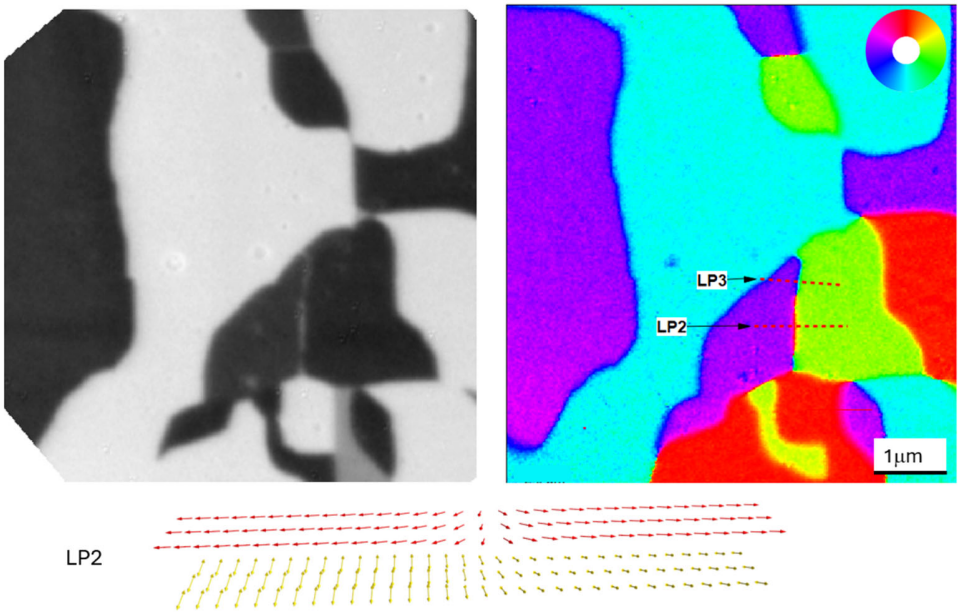


Fig 1. XMLD PEEM image of the LFO AF domains and domain walls (left), XMCD vector map of the LSMO FM domains (right) and 3d reconstruction of the AF/FM axes across the LP2 line profile.

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P-042 Student

Ultrafast Dynamics of epitaxial InAs/Al-rings Nanowires studied by Time Resolved Photoemission Electron Microscopy

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Metal-semiconductor hybrid architectures, particularly epitaxial Aluminum (Al) rings on Indium Arsenide (InAs) nanowires (NWs) govern charge transfer, plasmonic enhancement, and ultrafast carrier dynamics, pivotal for the development of topological quantum devices and high-speed nanophotonic devices [1,2]. Despite their potential, the ultrafast near-field dynamics and role of the epitaxial interface in modulating light-matter interactions at the nanoscale remain poorly understood. Here we investigate the near-field optical behavior of epitaxially grown aluminum ring structures on InAs NWs using time-resolved photoemission electron microscopy (PEEM). By systematically rotating the linear polarization of incident few-cycle near-infrared (NIR) pump pulses followed by UV probe pulses, we map the azimuthal distribution of photoemitted electrons and extract the local electric-field enhancement at the InAs/Al interface with nanometer spatial and sub-20-femtosecond temporal resolution. Our measurements reveal strongly anisotropic near-field localization dictated by the ring geometry and crystallographic orientation of the epitaxial contact, with increased electron yield when the pump polarization is aligned with the NW axis. Finite-difference time-domain simulations were performed, taking into account the interactions of both the NIR and the UV pulses with the InAs/Al structures. These findings establish epitaxial InAs/Al-rings NWs as a tunable platform for polarization-controlled hot-electron generation and provide insights into nanoscale spatio-temporal control of electronic states, informing the design of coherent quantum components and ultrafast plasmonic sensors.

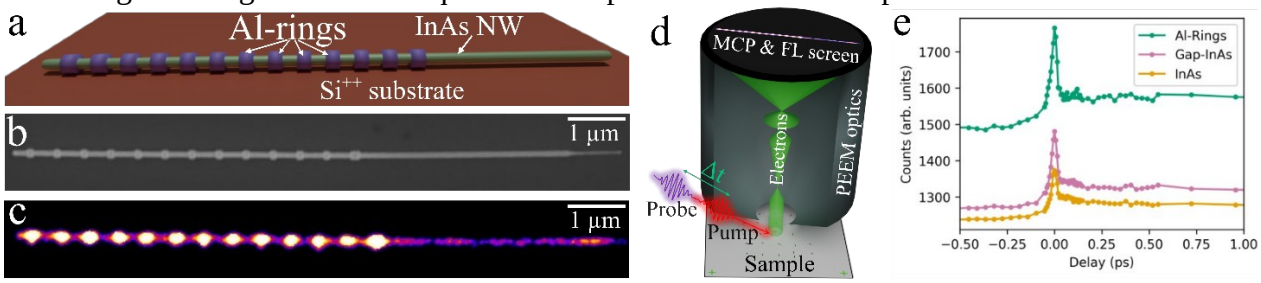


Fig 1. InAs/Al-rings NW: 3D model **(a)**, electron micrograph **(b)**, in PEEM **(c)**. **d:** Experiment schematic. **e:** Results showing a distinct difference between Al-rings and the exposed InAs.

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P-043 Student

Visualizing Oxygen Vacancy-Driven Orbital-Nematic Domains at the Surface of $SrMO_3/SrTiO_3$ Systems

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Oxygen vacancies are representative defects that strongly influence the physical properties of transition metal oxides. In many cases, they are treated as randomly distributed carrier dopants or sources of disorder[1]. In reality, however, an oxygen vacancy can also act as an oriented defect that distorts the surrounding lattice[2]. Such defect orientation can break local symmetry and may induce directional electronic states [3]. However, in transition-metal oxides, it remains largely unclear what real-space patterns such local symmetry breaking forms and how these patterns vary with the transition-metal d orbitals.

Here, we studied the real-space anisotropy of electronic states associated with oxygen vacancies on $SrMO_3$ (M = Nb, Ta) thin films grown on $SrTiO_3$ using laser-based photoemission electron microscopy (Laser-PEEM). After flash annealing at 720 °C in ultrahigh vacuum, PEEM images were obtained at room temperature with a linearly polarized laser with a wavelength of 266 nm.

Labyrinth- and droplet-like linear dichroism (LD) domains were observed on $SrNbO_3$ and $SrTaO_3$ surfaces respectively, developing along directions rotated ~45° from the crystal axes. This behavior cannot be explained by lattice mismatch alone and suggests an in-plane anisotropic electronic response linked to oxygen vacancies. Replacing Nb with Ta enhanced the LD intensity and altered the domain morphology, indicating a clear M-site dependence of the anisotropic response. Our results suggest that oxygen-vacancy-induced electronic anisotropy appears not only as a local defect effect, but also as mesoscopic domains at $SrMO_3$ surfaces, whose intensity and morphology depend on the transition-metal ion M.

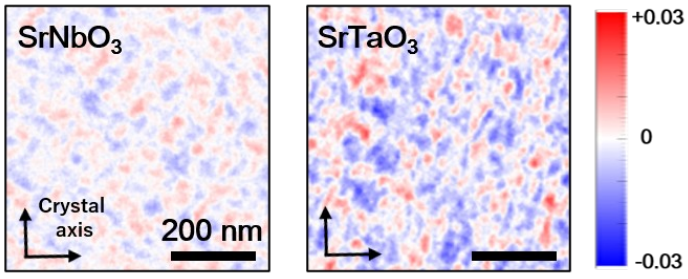


Fig 1. LD images of $SrNbO_3$ and $SrTaO_3$

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P-044

Dynamic Observation of Topological Domain Walls in Epitaxial Graphene Driven by Lithium Intercalation Using Low-Energy Electron Microscopy

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Engineering the stacking order of van der Waals (vdW) materials is a powerful approach for controlling their electronic and topological properties [1–3]. Here, we investigate lithium intercalation into epitaxial graphene grown on SiC(0001) using *in situ* aberration-corrected low-energy electron microscopy (LEEM). Bright-field and dark-field LEEM [4] combined with micro-LEED directly visualize intercalation-driven stacking evolution in real time [5].

Dark and bright-field LEEM reveal that Li intercalation proceeds selectively as shown in Fig. 1. Li atoms are first intercalated at AA-stacking topological crossing points (TCPs) and then propagate into neighboring AB domains. Density-functional theory and molecular dynamics calculations reproduce this sequence, showing that lithium energetically favors AA, followed by AB and BA stackings.

Li intercalation further drives a local AB-to-AA stacking transition, leading to the dynamic evolution of topological domain walls (TDWs). While TCPs remain fixed, surrounding TDWs move collectively to reconstruct the stacking-domain network without merging or annihilating, demonstrating their topological robustness.

These observations establish dynamic TDWs as a new class of intercalation-driven topological structures in vdW materials. *In situ* LEEM provides direct insight into stacking topology and enables dynamic stacking engineering for future quantum devices.

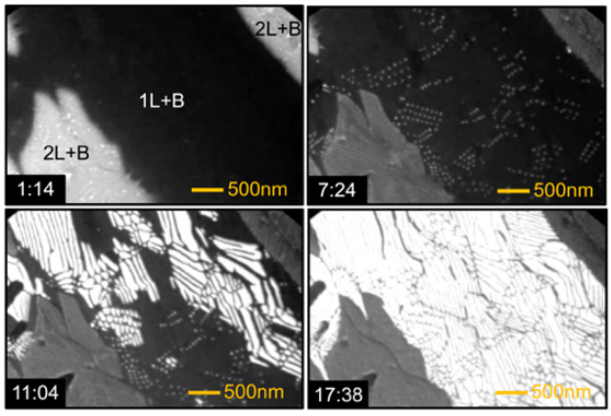


Fig 1. Li deposition time evolution and changes in the bright-field image. "1L(2L)+B" means monolayer (bilayer) graphene + buffer layer. The contrast is reversed with transferring to AA stacking by Li-intercalation.

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P-045

Phase transitions and reconstructions on ferroelectric perovskite surfaces

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Ferroelectric polarization in bulk crystals is a well-established phenomenon, however, its manifestation at surfaces remains far less understood. Electric fields generated by ionic displacements are significantly modified by surface reconstruction, atomic buckling, and changes in electronic structure. To exploit spontaneous polarization of ferroelectrics in photo- and piezocatalysis, a comprehensive model describing its actual influence at surfaces is required.

Here, we investigate oxide perovskites, one of the most important classes of stable catalytic materials known for their record-high efficiencies in water splitting [1]. A detailed analysis of surface ferroelectricity in single crystals of as-cleaved $BaTiO_3$(001), $KNbO_3$(001), and quantum paraelectric $KTaO_3$(001) reveals phenomena spanning both atomic and macroscopic length scales [2]. Polarized optical microscopy provides information on bulk polarization, while SEM imaging resolves 90° ferroelectric domains, typically 5 - 20 μm wide and extending up to several hundred μm in length. Contact AFM and PFM enable detection of smaller 180° domains via piezoresponse and friction signals. Furthermore, qPlus nc-AFM resolves the atomic arrangement of (1×1) surface structures in all studied perovskites.

Since the above methods probe ferroelectric surfaces only at fixed temperatures, LEEM measurements are employed to track structural evolution across phase transitions—for example, from the non-centrosymmetric tetragonal phase of $BaTiO_3$(001) to the cubic paraelectric phase. All structures are analyzed in both real and reciprocal space during annealing and cooling. Additionally, the possibility of modifying surface structures via high-temperature reduction under low oxygen partial pressure is investigated for tetragonal $LiNbO_3$(0001), where the formation of faceted $LiNb_3O_8$ and, ultimately, NbO_2 nanostructures is observed. Due to their submicrometer size, μLEED is employed to probe the crystal structure, revealing diffraction spots associated with nanocrystalline $LiNb_3O_8$ moving with beam energy. From these data, the surface slope and unit cell of the reconstruction are determined.

This research was supported by the Polish National Science Centre,
project SONATA 2022/47/D/ST5/02439.

References

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P-046 Student

Multimode Front-lens for Suppressing Space-Charge and Field-emission Effects in Time-Resolved Momentum Microscopy

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Time-resolved momentum microscopy has emerged as an indispensable technique for investigating the non-equilibrium dynamics of the electronic structure in solid-state systems [1]. However, its full potential is often constrained by space-charge effects: pump-induced space charge can hinder full access to fluence-dependent phenomena, such as photo-induced phase transitions with a switching threshold [2], while probe-induced space charge limits the achievable acquisition rate. To overcome these limitations, we employ a multimode momentum microscope with a newly designed cathode immersion front lens [3, 4]. This architecture enables control over both the strength and orientation of the electric field in front of the sample, giving access to three distinct operation modes: extractor, gap-lens, and repeller mode, Fig 1. By reducing the local field strength, or even applying a retarding field, these modes provide a new degree of freedom to suppress field emission and mitigate space-charge effects.

In the future, we aim to systematically compare probe- and pump-induced space-charge effects under different lens operation modes, demonstrating that the new front-lens substantially relaxes space-charge limitations in time-resolved momentum microscopy, opening a route towards higher-fluence, access to stronger photoexcitation regimes, and more field-sensitive measurements of ultrafast electronic dynamics.

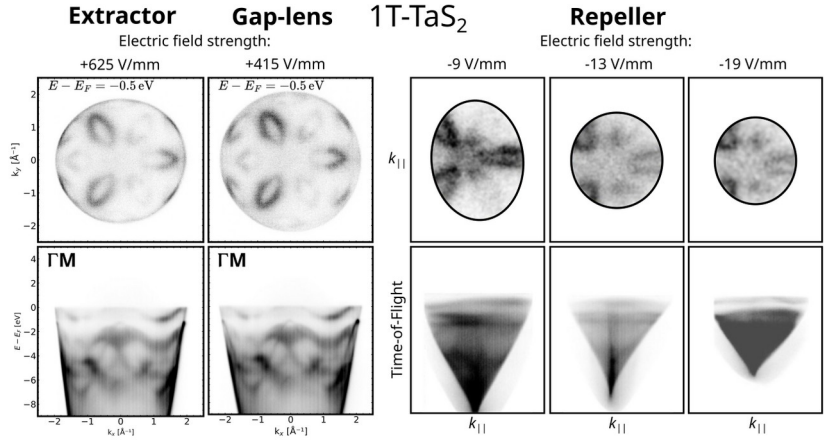


Fig 1. Demonstration of the different operating modes at varying field strengths on 1T-TaS_2.

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P-047

LEEM Imaging of Interfacial Coupling in Molecular Epitaxy on Graphene/SiC

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Organic molecular layers on graphene provide an ideal model platform for studying intermolecular interactions, epitaxial self-assembly, and charge transfer in hybrid low-dimensional systems. In particular, understanding the structural coupling at the interface is crucial for tailoring the properties of highly ordered molecular systems. Here, we investigate the growth and phase evolution of 2,3,6,7,10,11-hexamethoxytriphenylene (HMTP) on epitaxial graphene on SiC, focusing on how graphene–substrate coupling governs molecular diffusion and thin film formation.

Using in situ low-energy electron microscopy and diffraction (LEEM/LEED), complemented by X-ray diffraction, we provide real-time insights into the nucleation and growth kinetics. We show that HMTP forms highly ordered epitaxial layers on single-layer graphene, while growth on the covalently bound buffer layer proceeds through a disordered phase and yields weakly textured polycrystalline films (Fig. 1). By utilizing hydrogen intercalation to electronically decouple the graphene from the SiC substrate, we demonstrate that the restored long-range epitaxial ordering can be directly monitored via LEEM. Finally, we demonstrate highly ordered HMTP film growth on technologically relevant graphene platforms, proving the robustness of the mechanism and the versatility of these heterostructures for future device integration.

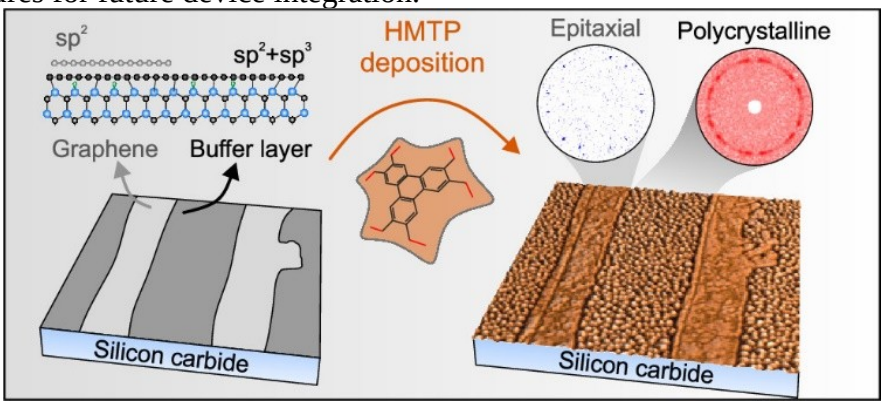


Fig. 1. Surface structure of graphene/SiC. Molecular deposition results in epitaxial growth on single-layer graphene and polycrystalline growth on the buffer layer. [1]

Reference

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P-048

TOF MARIS: a modular time-of-flight momentum microscope with high-pass filtering for clean delay-line detection

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The TOF MARIS is a real space and momentum space microscope, that has a time of flight filter in order to achieve spectroscopic data. In a drift tube, where the electrons are kept to a low kinetic energy, the electrons can separate in time according to their kinetic energy and are then detected by a position- and time-sensitive delay-line detector (DLD). With pulsed sources, a full energy window of laterally or angle-resolved distributions is acquired in parallel – an efficient alternative to band pass filters as in the NanoESCA MARIS. The MARIS lens reaches a lateral resolution of 35 nm and a momentum resolution better than 0.005 $Å^{-1}$, the TOF detector an energy resolution of 23.5 meV.

We show results of a new double-grid high-pass filter integrated in front of the DLD. In TOF detection the abundant low-energy secondary electrons share the drift section with the photoelectrons of interest, consuming detector count rate and degrading the dynamic range. By biasing the sample voltage relative to the grid potential, the filter systematically suppresses this secondary background. The energy spectra show the secondary contribution being progressively cut off, improving the signal-to-noise ratio and freeing dynamic range for the relevant photoelectrons – a decisive advantage for measurements with low repetition rates of the pulsed excitation source.

TOF MARIS is fully modular: the MARIS objective lens can be operated with a TOF energy filter or a double-hemispherical filter (NanoESCA MARIS), and either can be upgraded to the other. Combining both (XTOF) provides a 3 eV wide energy band-pass measured in parallel with the TOF detector, ideal for pulsed high-energy light sources (e.g. HHG or synchrotron).

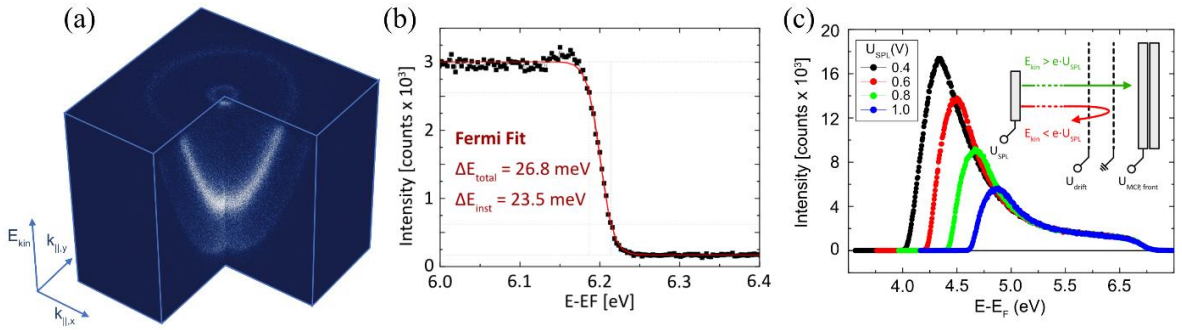


Fig 1. Parallel momentum vs. energy measurement of Ag(111), excited with a 3.1 eV laser (2PPE)(a), measurement of the Fermi edge (sample temperature 45 K) (b). Secondary cut off with high-pass filter for DLD (c).

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P-049

Strain-Induced Manipulation of Candidate Weyl States in W-Doped $MoTe_2$

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The electronic structure of transition metal dichalcogenides attracts a great deal of scientific interest due to the strong coupling between the lattice and electronic states. The electronic structure of type-II topological Weyl semimetals has been reported for Td - $MoTe_2$ using angle-resolved photoemission spectroscopy (ARPES).

Here, we present a comprehensive electronic structure study of W-doped $MoTe_2$ ($Mo_{0.91}W_{0.09}Te_2$) under uniaxial mechanical strain using soft and hard X-ray ARPES (HARPES).

High-resolution soft X-ray ARPES measurements, performed at the P04 beamline of PETRA III (DESY), confirm that partial tungsten substitution successfully stabilizes the hard-to-achieve low-temperature orthorhombic Td phase, yielding electronic bulk states similar to those of Td - $MoTe_2$. Tungsten doping simultaneously increases the overall spin–orbit coupling strength, inducing larger band gaps and elongating the candidate topological Weyl-state Fermi arcs.

HARPES measurements were performed at the P22 beamline using a hard X-ray time-of-flight momentum microscope end-station (HarMoMic). Applying uniaxial strain parallel to the a-axis causes depletion of heavy flat-band electronic states with high scattering rates near the Γ point, aligning with previous findings on $MoTe_2$. Conversely, our transport measurements demonstrate that strain applied along the b-axis significantly increases electrical resistivity.

These results provide direct experimental verification that mechanical strain can be used as a clean, reversible tool to manipulate bulk topological states in transition metal dichalcogenides.

P-050 Student

Low-energy electron microscopy study of the growth of $M_2Mo_3O_8$ (M = Mn, Fe) on Mo (110)

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The ternary molybdenum oxides $M_2Mo_3O_8$ (M = 3d transition metal, TM) are a model system for studying multiferroic properties. They crystalize in an intrinsically polar $P6_3mc$ structure and order magnetically at low temperatures, the polarity strongly coupled to the M^{2+} sublattice ordering, giving rise to a large, tunable magnetoelectric effect strongly dependent on the TM cation.

We present a low-energy electron microscopy (LEEM) study of the high-temperature, oxygen-assisted growth of $Mn_2Mo_3O_8$ and $Fe_2Mo_3O_8$. The compounds were synthesized by depositing the TM only, with the Mo (110) substrate acting as a source of Mo^{4+} cations. A similar phenomenon was previously observed for tungsten, forming $M^{II}WO_4$ on a W (110) surface;[1,2] to our knowledge, this has never been reported for molybdenum.

Low-energy electron diffraction (LEED) shows that the $M_2Mo_3O_8$ islands and wires grow preferentially along the [001] and [111] directions of Mo (110). Laterally resolved X-ray photoemission electron microscopy (XPEEM) confirms the presence of Mo^{4+} and reveals the coordination and bonding of both cations via the relevant absorption edges. Polarized Raman spectroscopy confirms the crystal symmetry and accessible phonon modes, and AFM images complete the morphological study.

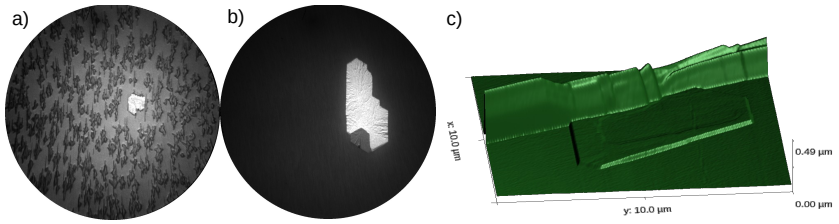


Fig 1. a) $Fe_2Mo_3O_8$ b) $Mn_2Mo_3O_8$, FOV: 15 µm in both cases. c) $Mn_2Mo_3O_8$ island + wire, AFM.

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P-051

First Application of Binary Pseudo-Random Arrays to XPEEM: Resolution Calibration and Lens Distortion Correction

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X-ray photoemission electron microscopy (XPEEM) is a powerful tool for full-field spectroimaging, yet its ultimate spatial resolution is inherently constrained by real-world physical processes and complex electron-optical lens aberrations. Thoroughly evaluating these imaging systems over their entire dynamic application range remains a challenge due to the limitations of traditional, localized calibration targets. In this work, we demonstrate the first application of binary pseudo-random array (BPRA) test standards—originally pioneered by Lawrence Berkeley National Laboratory (LBNL)—to calibrate and optimize an XPEEM instrument. Unlike conventional targets, BPRA patterns are deterministic structures engineered to possess a constant, inherent "white-noise" power spectral density (PSD). By recording an XPEEM image of the BPRA target and analyzing its spectral deviation from the flat ground-truth PSD, we successfully extract the complete two-dimensional Instrument Transfer Function (ITF) of the system over its entire field of view and spatial frequency range. This approach proves exceptionally powerful for isolating local lens imperfections and providing the precise feedback necessary for correcting complex stigmations. Ultimately, this methodology establishes a robust, hardware-independent framework for quantitative resolution calibration, paving the way for automated aberration correction and beyond-resolution image reconstruction in full-field electron metrology.

P-052 Student

Momentum Microscopy of Gated Monolayer TMDs

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Monolayer (1L) transition metal dichalcogenides (TMDs) are promising candidates for next-generation semiconductor devices due to their unique optical, electronic, and spin-valley properties. Harnessing these properties requires understanding of the electronic states of these materials. Momentum microscopy (MM) has proven to be a powerful technique [1] to study 1L TMDs due to its real-space imaging capabilities, providing the spatial resolution necessary to probe microscopic, exfoliated samples. Furthermore, MM allows for the mapping of band structures across the entire Brillouin zone, enabling the tracking of carriers across distinct valleys [2,3]. In this presentation, we demonstrate the electrostatic gating of 1L TMDs within a momentum microscope setup, facilitating the direct observation of these materials' electronic properties, such as quasiparticle bandgap, in the presence of doped charge carriers.

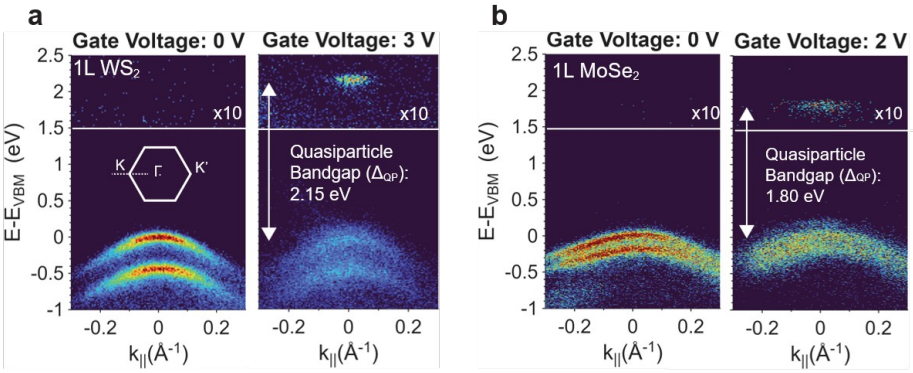


Fig 1. Gate-dependent ARPES spectra of a) 1L WS_2 and b) 1L $MoSe_2$ wherein the application of a gate voltage induces a population of doped carriers.

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P-053 Student

Low-energy electron exposure of trinuclear tin complex EUV resist

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Extreme ultraviolet lithography (EUVL) is the state of the art in lithography, capable of projecting sub-10nm features onto photoresists. EUVL produces a low photon flux of high-energy photons (13.5nm/91.7eV), which creates a significant secondary electron (SE) cascade within the resist. This leads to stochastic effects, specifically photon shot noise and an isotropic SE blur around the photon absorption sites. The SE blur and photon shot noise are key factors in EUVL; both play an important role in the resolution, line-edge roughness, and sensitivity (RLS) trade off. It is the SEs that are responsible for the solubility switch of the resist; their distribution throughout the resist is what matters in the end. Our research aims to better understand the role of the SEs and investigates ways of manipulating them. For this, LEEM is used as a controlled exposure platform to vary both dose and landing energy, like in our previous work [1,2]. Our current investigation extends this approach to a trinuclear tin complex (TTC) resist, an EUV resist developed at Korea University [3]. Our research program works towards an electric field application to manipulate the SE blur anisotropically to further optimize the RLS metrics. Here we show results of LEEM exposure on TTC without field application, where TTC was exposed to a matrix of dwell spots and subsequently analyzed with AFM. This provides us with the baseline for future experiments on EUV resists with an electric field applied.

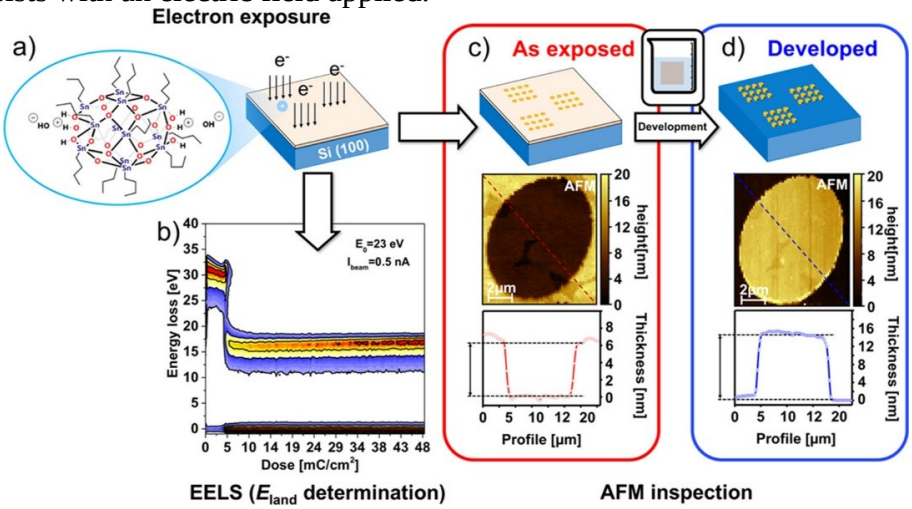


Fig 1. (a) TinOH MOR. (b) EELS spectrum. (c,d) Post-exposure and post-development AFM images of a dwell spot. Figure 1 from reference showing key experimental steps [2].

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Classified as | Confidential - Vertrouwelijk

P-054

Ultrafast SPLEEM and LEEM

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Aberration corrected spin-polarized low-energy electron microscopy (AC-SPLEEM) enables magnetic imaging with nanometer spatial resolution and high surface sensitivity [1], but conventional instruments are limited to quasi-static measurements [3]. We designed an ultrafast SPLEEM that integrates femtosecond pump–probe techniques to study magnetic dynamics on picosecond timescales [2]. Femtosecond/picosecond laser pulses excite the sample and generate ultrashort spin-polarized electron pluses, allowing time-resolved imaging of transient magnetic structures. Key challenges include preserving spin polarization, minimizing space-charge effects, and synchronizing ultrafast laser and electron pluses. The resolution in ultrafast mode can achieve 9nm at 12ps. It will enable direct observation of ultrafast demagnetization, spin transport, and domain dynamics in nanoscale magnetic materials.

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