HL 18: Focus Session: Nanoscale Light-matter Interaction I

The focus session highlights recent breakthroughs in resolving the optoelectronic properties of individual nanostructures down to the atomic scale. Moreover, the session introduces the rich field of surface polaritons, confined electromagnetic modes through which light can be guided on subwavelength scales.

The focus session is organized by Markus Huber (U Regensburg) and Fabian Mooshammer (U. Regensburg).

Time: Tuesday 9:30–13:00 Location: H17

Invited Talk HL 18.1 Tue 9:30 H17
Ultrafast Nano-Spectroscopy of Photo-Induced Dynamics in Low-Dimensional Materials — •Takashi Kumagai — Institute for Molecular Science, Okazaki, Japan

Low-dimensional semiconductors have been extensively studied as platforms for fascinating physics and as potential components for quantum nano-devices. Their low dimensionality leads to unique physical properties, driven by strong quantum confinement and reduced dielectric screening. However, this also renders low-dimensional materials highly sensitive to local structures and interactions with their surroundings. To fully understand their superior properties, it is essential to investigate their local structures and how they correlate with photo-induced dynamics. Recently, ultrafast infrared nano-spectroscopy based on scanning near-field optical microscopy (IR-SNOM) has emerged as a powerful tool to directly visualize local structures and dynamics in real time and space at the nanoscale. I will present our latest research to apply ultrafast IR-SNOM to explore nanoscale photo-induced dynamics in low-dimensional materials [1]. In single-layer transition metal dichalcogenides, we have visualized the local many-body dynamics of high-density electron-hole plasma, uncovering the significance of dynamic heterogeneity linked to the non-uniform optoelectronic properties. Furthermore, we have extended ultrafast IR-SNOM to study local exciton dynamics in single-walled carbon nanotubes (SWCNTs). Within individual, isolated SWCNTs, the non-uniform formation of electron-hole pairs is correlated with local strain. [1] Y. Wang, J. Nishida et al. ACS Photonics, accepted.

Invited Talk HL 18.2 Tue 10:00 H17
Landau level Nanoscopy of charge and heat transport in low-dimensional heterostructures — •Mengkun Liu — Stony Brook University

In contemporary condensed matter physics and photonics, four key length scales play an essential role in shaping the behavior of quantum materials: (1) the polaritonic wavelength, which governs light confinement and light-matter interactions; 2) the magnetic lengths, determined by the magnetic field B, which constrains electron motion; 3) the diffusion length of the hot carriers at interfaces and the edges, which dictates energy relaxation, and 4) the periodicities of superlattices induced by moiré engineering, which defines the energy scale of emerging quantum phases. For instance, the commensurability of the magnetic lengths (~10 nm for graphene at 7T) and superlattice constant (~10 nm for twisted bilayer graphene at "magic" angle) would give rise to exotic fractal quantum states. In this talk, I will present: 1) A cutting-edge optical spectroscopy technique, Landau-level nanoscopy, capable of simultaneously probing all four critical length scales in a single experiment; 2) the discovery of classes of infrared polaritons that can be tuned by magnetic fields, enhancing our ability to manipulate light-matter interactions and probe many-body physics at the nanoscale; 3) nanoscale mapping of thermoelectric properties in the quantum Hall bulk, revealing strong violations of the Wiedemann-Franz law. Our approach establishes Landau-level nanoscopy as a versatile platform for investigating magneto-optical effects and many-body interactions at the nanoscale.

Invited Talk HL 18.3 Tue 10:30 H17
Real space mapping of electrically tunable anisotropic THz plasmon polaritons in hBN encapsulated black phosphorus — •Eva Pogna — Institute of Photonics and Nanotechnology, CNR-IFN, Milan, Italy

Polaritons in two-dimensional layered crystals offer effective means to confine and manipulate terahertz (THz) electromagnetic waves at the nanoscale, a crucial step in advancing photonic technologies.

In this study, we investigate anisotropic plasmon polaritons in black phosphorus nanoflakes at THz frequencies, utilizing near-field photocurrent nanoscopy combined with THz hyperspectral near-field scattering techniques.

Encapsulation with hexagonal boron nitride protects black phosphorus from air-induced degradation, while field-effect transistor (FET) devices enable photo-thermoelectric detection of plasmon polaritons.

Our findings reveal highly confined, gate-tunable plasmon polaritons with subwavelength dispersion ($\sim \lambda/76$ at 2.01 THz).

The dielectric anisotropy of black phosphorus leads to polaritons with elliptic wavefronts at THz frequencies, enabling enhanced confinement and control over THz field propagation. Moreover, electrostatic control of carrier density allows precise tuning of polariton wavelength, highlighting the versatility of this platform for nanoscale THz light manipulation and reconfigurable infrared nanophotonics.

Notably, the four-gate FET architecture introduced here to examine in-plane propagation anisotropy can be readily adapted for the study of other anisotropic conductive materials.

15 min. break

Invited Talk HL 18.4 Tue 11:15 H17
Ultra-confined THz hyperbolic phonon polaritons in a transition metal dichalcogenide — Ryan A. Kowalski[1], Niclas S. Mueller[2], Gonzalo Alvarez-Perez[3], Maximilian Obst[4], Katja D. Granados[1], Giulia Carini[2], Aditha Senarath[1], Saurabh Dixit[1], Richarda Niemann[1,2], Ragu B. Iyer[5], Felix Kaps[4], Jakob Wetzel[4], J. Michael Klopf[6], Ivan I. Kravchenko[7], Deliang Bao[1], Sokrates T. Pantelides[1], Martin Wolf[2], Lukas Eng[4], Pablo Alonso-Gonzalez[3], Susanne Kehr[4], Thomas G. Folland[5], •Alexander Paarmann[2], and Joshua D. Caldwell[1] — [1]Vanderbilt University, Nashville, TS, USA — [2]Fritz Haber Institute of the Max Planck Society, Berlin, Germany — [3]University of Oviedo, Oviedo, Spain — [4]TUD Dresden University of Technology, Dresden, Germany — [5]The University of Iowa, Iowa City, IA, USA — [6]Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany — [7]Oak Ridge National Laboratory, TN, USA

Phonon polaritons are hybrid light-matter quasiparticles in polar crystals that enable waveguiding of light on length scales much smaller than the photon wavelength. Here, we introduce $HfSe_2$ as a new van der Waals material that supports phonon polaritons in the terahertz (THz) spectral range. Using THz near-field optical microscopy, we demonstrate extreme confinement of light from 61 μm free-space wavelength to 245 nm. We show that the origin of this record-high confinement is an exceptionally large light-matter coupling of hyperbolic $HfSe_2$.

Invited Talk HL 18.5 Tue 11:45 H17
Programmable polariton nanophotonics using phase-change materials — •Thomas Taubner — I. Institute of Physics (IA), RWTH Aachen University, Aachen, Germany

Tailoring light-matter interaction is essential to realize nanophotonic components and can be achieved with polaritons, an excitation of photons coupled to charges in metals and semiconductors. Adding a thin layer of Phase-change material (PCM) leads to stronger polariton confinement and enables optical writing of resonator structures based on a change in the refractive index [1]. The recently introduced plasmonic PCM In_3SbTe_2 (IST) can be reversibly switched from an amorphous dielectric to a crystalline metallic state, enabling optically re-writable IR nanoantennas and metasurfaces [2].

Here, we show direct optical writing of resonators for surface phonon polariton (SPhP) by crystallizing IST on top of a SiC crystal and investigate the strongly confined resonance modes with s-SNOM. Reconfiguring the size and shape of the resonators leads to mode confinements of $\lambda/35$ [3]. We also demonstrate the real-space imaging of IR surface plasmon polaritons on bulk doped semiconductors, enabled by the strong polariton confinement induced by the added thin dielectric PCM layer [4]. Our concept allows for the rapid prototyping of reconfigurable structures for polaritonics, especially useful with anisotropic

2d materials.

[1] Li et al., *Nat. Mat.* **15**, 870 (2016) [2] Heßler et al. *Nat. Com.* **12**, 924 (2021) [3] Conrads et al. *Nat. Com.* **15**, 3472 (2024) [4] Conrads et al. *Sci. Adv. under review*

HL 18.6 Tue 12:15 H17

Heralding non-classical light by tailored free-electron interactions with photonic modes — •Armin Feist[1,2], Guanhao Huang[3,4], Germaine Arend[1,2], Yujia Yang[3,4], Jan-Wilke Henke[1,2], Zheru Qiu[3,4], Hao Jeng[1,2], Arslan Sajid Raja[3,4], Rudolf Haindl[1,2], Rui Ning Wang[3,4], Tobias J. Kippenberg[3,4], and Claus Ropers[1,2] — [1]Max Planck Institute for Multidisciplinary Sciences, Göttingen, DE — [2]4th Physical Institute, University of Göttingen, DE — [3]Institute of Physics, EPFL, Lausanne, CH — [4]Center for Quantum Science and Engineering, EPFL, Lausanne, CH

Integrated photonics facilitates control over fundamental light-matter interactions in manifold quantum systems. Extending these capabilities to electron beams [1] fosters free-electron quantum optics.

Here, we show the coupling of single electrons and photons at an integrated photonics waveguide [2,3]. Spontaneous scattering of the nanoscale-focused electron beam at empty optical modes creates multiphoton superposition states. Energy-selective and event-based electron detection enables heralding non-classical light, which we characterize by intensity correlations in a Hanbury Brown and Twiss (HBT) setup, showing high-fidelity single-photon generation [3].

This provides a pathway toward novel hybrid quantum technology with entangled electrons and photons, as well as the capability for quantum-enhanced electron imaging and Fock-state photon sources.

[1] J.-W. Henke *et al.*, Nature **600**, 653 (2021). [2] A. Feist *et al.*, Science **377**, 777 (2022). [3] G. Arend *et al.*, arXiv:2409.11300 (2024)

HL 18.7 Tue 12:30 H17

Attosecond electron microscopy using free-electron homodyne detection — •John H. Gaida[1,2], Sergey V. Yalunin[1,2], Hugo Lourenço-Martins[1,2], Murat Sivis[1,2], Thomas Rittmann[1,2], Armin Feist[1,2], F. Javier García de Abajo[3,4], and Claus Ropers[1,2] — [1]MPI for Multidisciplinary Sciences, Göttingen, Germany — [2]4th Physical Institute, University of Göttingen, Germany — [3]ICFO-Institut de Ciencies Fotoniques, Castelldefels (Barcelona), Spain — [4]ICREA-Institució Catalana de Recerca i Estudis Avançats, Barcelona, Spain

Advancements in condensed matter science aim to map material structures and dynamics at levels of ångströms and attoseconds. Although X-ray and electron methods offer structural detail, attosecond temporal resolution is progressing through optical spectroscopy techniques. Techniques like PINEM allow nanometric resolution imaging of near-field intensities [1], but to examine the evolution of nanoscale fields and structures within the light cycle, optical phase sensitivity is needed, as provided by phase-contrast Lorentz PINEM [2], interferometric detection [3], or electron pulse bunching [4]. This contribution introduces Free-Electron Homodyne Detection (FREHD), a universally applicable approach for high spatiotemporal resolution imaging of phase-resolved optical responses [3].

[1] B. Barwick *et al.*, Nature **462**, 902–906 (2009). [2] J. H. Gaida *et al.*, Nat. Commun. **14**, 6545 (2023). [3] J. H. Gaida *et al.*, Nat. Photonics **18** 509–515 (2024). [4] K. E. Priebe *et al.*, Nat. Photon. **11**, 793–797 (2017).

HL 18.8 Tue 12:45 H17

Light-matter interaction on subcycle time and atomic length scales — •Tom Siday[1,2], Johannes Hayes[1], Felix Schiegl[1], Fabian Sandner[1], Peter Menden[1], Valentin Bergbauer[1], Martin Zizlsperger[1], Svenja Nerreter[1], Sonja Lingl[1], Jascha Repp[1], Jan Wilhelm[1], Markus A. Huber[1], Yaroslav A. Gerasimenko[1], and Rupert Huber[1] — [1]Department of Physics and Regensburg Center for Ultrafast Nanoscopy (RUN), University of Regensburg, Regensburg, Germany — [2]School of Physics and Astronomy, University of Birmingham, Birmingham, UK

Near-field microscopy has revolutionized the study of nanoscale light-matter interaction, achieving subcycle temporal and ~10 nm spatial resolution. However, the geometry of the tip apex has so far restricted access to atomic resolution. By harnessing extreme nonlinearities within tip-confined evanescent light fields, we introduce a novel contrast mechanism, advancing all-optical microscopy to the atomic scale while preserving subcycle temporal resolution. This Near-field Optical Tunnelling Emission (NOTE) microscope can resolve nanometer-scale packing defects on a gold surface and trace the subcycle quantum flow of electrons between the scanning tip and a semiconducting van der Waals trilayer in real time. Moreover, NOTE microscopy is compatible with insulating samples, where rectified currents cannot flow, and enables the integration of all-optical subcycle spectroscopy with atomic-scale resolution. Thus, NOTE provides direct access to atomic-scale quantum light-matter interactions and dynamics on their natural spatial and temporal scales.