HL 16: Focus Session: Quantum Emitters in 2D Semiconductors

Quantum emitters are fundamental building blocks in the development of scalable quantum communication networks. They provide capabilities for single-photon generation, quantum memory, and entanglement distribution*essential components for quantum key distribution, quantum repeaters, and future quantum internet infrastructure. Two-dimensional (2D) materials have recently emerged as a highly promising platform for quantum photonics. Their atomically thin nature enables strong light-matter interaction, high tunability, and seamless integration with photonic and electronic environments. Moreover, the reduced dielectric screening and strong excitonic effects inherent to 2D materials provide unique opportunities to engineer and control localized excitonic states that act as quantum emitters. This combination of physical richness and technological compatibility places 2D materials at the frontier between fundamental quantum optics and device-level quantum technologies. To advance the field, it is essential to understand both the microscopic theoretical principles and the engineering challenges associated with integrating such systems into communication networks.

Organized by Michael Lorke, Iris Niehues and Tobias Heindel

Time: Tuesday 9:30–12:45 Location: POT/0081

Invited Talk HL 16.1 Tue 9:30 POT/0081

Tailoring the performance of WSe_2 quantum emitters via cavity quantum electrodynamics and coherent driving — •Ivan Solovev — Institute of Physics, Carl von Ossietzky University of Oldenburg, Oldenburg, Germany

The ability to create scalable arrays of bright and easily-fabricated single photon sources has sparked keen interest in Van der Waals materials, rendering them a promising platform for emerging quantum technologies. Here I will provide an overview how their performance can be substantially improved via integration into a tunable microcavity as well as exploiting resonant excitation schemes. The implementation of the monolithic Fabry-Pérot open cavity, operating in a weak coupling regime, enables the observation of phenomena such as Purcell enhancement of radiative decay, strain-induced tuning of the emitter energy and two-photon interference. An impact of phonons on dephasing and resulting indistinguishability will be discussed. Furthermore, the selective excitation in a coherent manner is achieved via resonant driving, leading to the observation of Rabi oscillations.

Invited Talk HL 16.2 Tue 10:00 POT/0081

Deterministic single-photon emitters in 2D materials — •Ursula Wurstbauer — University of Münster, Germany

Single-photon emitters (SPEs) play a pivotal role as building blocks for quantum technologies. In two-dimensional (2D) materials, SPEs can deterministically be generated, externally manipulated and monolithically integrated. The properties of SPEs in atomically thin membranes are strongly dependent on the host materials and differ e.g. between TMDCs and hBN but also on the emitters origin, like defects, strain or moiré-potentials in twisted structures [1,2]. SPEs can be generated on-demand and on-chip with high lateral precision in the prototypical TMDC monolayer MoS2 by defect engineering utilizing focused helium ions [3]. These defect states in TMDCs interact with the electronic bands, whereas some defects in hBN show color center like behavior [1]. Following a general introduction, we focus on generation and characterization of rather monoenergetic SPEs in hBN by Argon ion irradiation [4]. We gratefully acknowledge A. R. Bhuiyan, R. Schmidt, A. Michaelis de Vasconcellos, R. Bratschitsch and Harry Mönig for fruitful collaboration. [1] S. Michaelis de Vasconcellos et al. Physica status solidi b259, 2100566 (2022). [2] M. Brotons-Gisbert, et al. MRS Bulletin 49, 914-931 (2024). [3] J. Klein et al. ACS Photonics, 8, 2, 669-677 (2021). [4] A. R. Bhuiyan et al.

Invited Talk HL 16.3 Tue 10:30 POT/0081

Resolving atomic and electronic structure of point defects in MoS_2 by first-principles calculations and scanning tunneling microscopy — •Hannu-Pekka Komsa — University of Oulu, Oulu, Finland

A unique advantage of 2D materials is that the defects in them are always at or very near to the surface, which can be highly beneficial in quantum emitter and quantum sensing applications. Importantly, this also enables direct characterization and manipulation of the defects with surface-sensitive techniques, such as scanning tunneling microscopy (STM). Since STM probes mainly the electronic structure, defect identification often requires comparison to results from first-principles calculations.

I will present our recent investigations on the electronic structure of a few common point defects in 2D MoS_2, such as S vacancies, Mo and Fe adatoms, and C substitutional on S site, combining first-principles calculations and experimental STM results from University of Cologne and Karlsruhe Institute of Technology. I will first discuss the computational aspects that were found to be important in achieving good agreement with experiments. A careful analysis and comparison of the computational and experimental results then allow us to infer defect identity, charge state, defect-defect interactions, magnetic moment, and dynamic effects such as defect transformations among Jahn-Teller configurations, defect charging, and spin lifetimes. Finally, benefiting from the atomic manipulations inside STM, rational atom-by-atom fabrication of defect structures can be envisioned.

15 min. break

Invited Talk HL 16.4 Tue 11:15 POT/0081

Polarization dynamics of isolated defects in hexagonal boron nitride — Serkan Paçal[1], Çağlar Samaner[1], Furkan Ağlarci[1], Ömer S. Tapşin[1], and •Serkan Ateş[1,2] — [1]Department of Physics, Izmir Institute of Technology, Izmir, Turkey — [2]Faculty of Engineering and Natural Science, Sabanci University, Istanbul, Turkey

Single-photon sources (SPSs) are indispensable for quantum information technologies like Quantum Key Distribution. The practical success of these applications critically depends on the high purity and long-term stability of the emitted light's polarization state, which serves as the information-carrying quantum bit (qubit). Understanding and controlling polarization dynamics, therefore, presents a universal challenge for establishing reliable solid-state quantum interfaces. We propose using hexagonal Boron Nitride (hBN) defect centers as a promising new platform for SPSs exhibiting strong, stable single-photon emission at room temperature, making it an ideal model system. In this work, we specifically investigate the polarization properties of hBN defect centers. We analyze the dynamics and temperature dependence of the polarization degree, focusing on the influence of electron-phonon interactions. Our results offer crucial insights that enable the development of targeted strategies to enhance the polarization stability of single-photon emitters, thereby facilitating more robust quantum optical systems.

Invited Talk HL 16.5 Tue 11:45 POT/0081

Defect-driven quantum emission in 2D materials — •Magdalena Grzeszczyk — IFIM, NUS, 117544, Singapore

Carbon-doped hexagonal boron nitride (hBN:C) provides a compelling 2D analogue to classical wide-bandgap hosts such as ruby (Cr:Al2O3), where isolated impurity centers give rise to sharp, stable optical transitions. These point defects have emerged as robust and manipulatable single-photon emitters (SPEs). By combining a broad suite of experimental techniques with advanced theoretical modeling, we introduce a consistent assignment of the observed excitations in hBN:C to the most likely underlying defect complexes. The described defect states residing in close proximity to the surface present an ideal sensors of local fields at the nanoscale. An example of how the local dielectric environment strongly modulates these centers, producing distinct spectral shifts will be discussed. Additionally, these defect states can be electrically excited in hBN-based light-emitting diode structures, providing a route toward integrated quantum emitters in van der Waals devices. Finally, ZnPS3 will be introduced as an emerging new host of SPEs. As a representative member of a broader family of layered MPX3 compounds, such as MnPS3 and FePS3, this emergent host opens new platform for future exploration of SPEs with intrinsic magnetic tunability.

HL 16.6 Tue 12:15 POT/0081

Nanoscale magnetic field sensing with spin defects in hexagonal boron nitride — •Korbinian Felber, Timo Strobl, Paul Konrad, Andreas Sperlich, and Vladimir Dyakonov — Experimental Physics 6, Julius-Maximilians-Universität Würzburg (JMU), 97074 Würzburg, Germany

The development of quantum sensors based on solid-state spin defects is a vibrant research area, yet most host materials are three-dimensional, making it challenging to position the sensing spins in close proximity to a target sample. This limitation was recently overcome in 2020 with the discovery of the negatively charged boron vacancy (V_B^-) in the two-dimensional van der Waals material hexagonal boron nitride (hBN). Exfoliating spin-active hBN flakes provide coherent spin manipulation in an atomically thin host. Using optically detected magnetic resonance (ODMR), these hBN spin defects provide sensitive readout of local magnetic fields, temperature, and strain, making functional hBN layers an ideal platform for exploring fundamental questions in 2D magnetism. In this study, we assemble a vdW heterostructure by stacking active hBN on top of a 2D ferromagnet. By employing spin-relaxometry techniques, we probe nanoscale magnetic fluctuations near the Curie temperature of the exfoliated ferromagnet. Our results highlight the potential of hBN-based quantum sensors for characterizing local magnetic properties in vdW heterostructures, offering substantial benefits for the design of next-generation 2D devices.

HL 16.7 Tue 12:30 POT/0081

Ion-beam induced quantum emitters in hexagonal boron nitride — •Jan Böhmer, Annkathrin Köhler, Hannes Simon, Lucas Böhme, and Carsten Ronning — Friedrich Schiller University, Jena, Germany

Defect centers in solid-state materials are emerging as highly promising candidates for realizing robust quantum light sources. Among these, hexagonal boron nitride (hBN) has attracted significant interest due to its potential for hosting room-temperature single photon emitters (SPEs). We utilize ion-beam irradiation to introduce optically active defect centers into hBN, offering a controlled and tunable method for engineering defect centers. We have investigated intrinsic and extrinsic ion-beam induced defect centers in exfoliated hBN flakes: Micro-photoluminescence spectroscopy (μ-PL) was employed to characterize the spectral properties of the induced emitters, while second-order correlation measurements ($g^{(2)}$) were performed to demonstrate the single-photon emission behavior and determine the quantum nature of the sources. Additionally, in-situ electrical measurements were used to monitor the reaction of the hBN flakes to irradiation in real-time. The results demonstrate that ion-beam irradiation can be successfully utilized for creation of quantum emitters in hBN. This work contributes to the ongoing effort to develop reliable, solid-state single photon emitters for quantum applications.