2D Materials
Room 304 - Session 2D-WeM
2D Materials: Electronic, Magnetic, Mechanical, and Optical Properties

Moderators: Prof. Victor Brar, University of Wisconsin - Madison, **Souvik Sasmal**, Argonne National Laboratory

8:00am **2D-WeM-1 Functionalizing 2D Materials with Defects and Dopants Using Ultra-Low Energy Ions***, **Harriet Åhlgren**,* Uppsala University, Sweden

The inert surface plane of 2D materials can be functionalised by defects and the incorporation of foreign atomic species for applications in catalsysis, energy conversion and optoelectronics. Various methods are available for this, but major challenges still lay in the control of the defect types and their concentrations. Irradiation with energetic ions at ultra-low energies (< 100 eV) offers a powerful tool to create modifications with selected type and concentration in 2D materials by adjusting the kinetic energy of the ion and the exact number of the ions. In this talk, I will discuss our recent efforts in applying this methodology to functionalise and manipulate 2D materials. Specifically, I will review our recent results on introducing substitutional metal atoms in graphene [1,2], and how these functional sites are then used as anchoring sites to build single atom thick planar metal structures (metallenes) on the graphene surface [3]. Structural analysis via high-resolution transmission electron microscopy reveals the defect structures and metallenes at single atom scale, while atomistic simulations provide complementary information about at the dynamic processes of the synthesis at picosecons timescales.

[1] Trentino,.., Åhlgren et al. Micron 184, 103667, 2024.
[2] Trentino,.., Åhlgren, 2D Materials 9, 025011, 2022.
[3] Joudi, .., Åhlgren, ACS Nano 19, 22032-22043, 2025.

8:15am **2D-WeM-2 Clean Integration of h-BN Encapsulated Graphene Heterostructures with Ferroelectric $Al_{1-x}B_xN$ Thin Films for Robust Carrier Concentration Modulation***, **Joseph Hladik**,* Penn State University*; Aswini Ramankutty,* University of Pittsburgh*; K. M. Daiyan,* Penn State University*; Jeremy Levy, Patrick Irvin,* University of Pittsburgh*; Beth Dickey,* Carnegie Mellon University*; Morteza Kayyalha, Jon-Paul Maria,* Penn State University

Since the discovery of graphene, there have been significant efforts to manipulate its band structure to further probe its interesting properties. However known band structure engineering methods, such as nanostructuring, twistronics, and chemical doping, can present practical challenges and may degrade the delicate structure of graphene that brings about these interesting properties in the first place. A new platform for precise, nondestructive tuning of energy landscapes in graphene has been developed, which involves the interaction of graphene with the electrostatic field effect generated by a thin film of ferroelectric $Al_{1-x}B_xN$. Using resist-free ultra-low-voltage electron-beam lithography (ULV-EBL), ferroelectric domains can be patterned and reprogrammed through an existing graphene-to-AlBN interface at resolutions below 20 nm, where the graphene acts as a capacitor top electrode during writing. These ferroelectric domains in AlBN are highly robust, showing polarization of up to 130 $\mu C/cm^2$ and capable in principle of inducing theoretical carrier concentrations of up to 10^{15} cm^{-3} in an adjacent graphene layer. However, this limit of carrier modulation assumes the full polarization field has been screened by the graphene. To achieve this theoretical limit, interfacial contamination during device preparation must be eliminated so as to block alternative compensation paths. We have demonstrated the preparation of defect-free single layer graphene encapsulated with multilayer h-BN via a dry transfer method under argon atmosphere to prevent moisture accumulation between layers. This dry transfer method involves a PC film-assisted PDMS stamp for easy pickup and stacking of exfoliated flakes, as well as precise placement of full 2D heterostructures within defined device AlBN windows. Gold metal is used to make contact to encapsulated graphene via a 1D edge contacting method. In this presentation, we detail the specific process flow for the clean transfer of standalone 2D single layer graphene as well as 2D h-BN encapsulated graphene heterostructures onto $Al_{1-x}B_xN$ surfaces. Transport property measurements will be shown that measure the graphene carrier density and explore the modulation limits possible using the ferroelectric polarization.

8:30am **2D-WeM-3 Hidden in Plain Sight: Aromaticity of Hexagonal Boron Nitride***, Suryakanti Debata,* Laboratory for Physical Sciences*; Sai Krishna Narayanan,* University of Maryland College Park*; **Pratibha Dev**,* Laboratory for Physical Sciences **INVITED**

Hexagonal boron nitride (hBN), which is isoelectronic to graphene, is of interest for a wide range of applications in electronics, photonics, catalysis, and quantum information science. Despite this broad interest, it is not known if hBN is aromatic. Aromaticity (or lack thereof) of a planar structure is related to its structural and chemical stability, and hence, its determination is of fundamental importance to different applications. With the help of energetic and magnetic criteria, we determine the aromaticity of hBN flakes of different sizes. We show that although hBN is aromatic, it is weakly so as compared to graphene. Ultimately, the differences in the aromaticity of hBN and graphene can be linked to the differences in their symmetry-allowed transitions between the occupied and unoccupied molecular orbitals.

9:00am **2D-WeM-5 Damage-Free Fabrication of Single Photon Emitters in Hexagonal Boron Nitride by Remote Plasma Generation of Vacancies***, Souvik Bhattacharya, Swetapadma Sahoo,* University of Illinois Urbana-Champaign*; Simeon Bogdanov,* University of Illinois Urbana Champaign*; **R. Mohan Sankaran**,* University of Illinois Urbana-Champaign

Hexagonal boron nitride (hBN) has emerged as a promising material for quantum photonics and sensing because of its unique ability to host single room-temperature optically active color centers that exhibit bright and stable emission. However, scalable and deterministic fabrication of the emitters remains challenging. Color centers often appear near an edge or fold in the material, or require methods that produce undesired damage. Emitters are produced from combinations of impurities and vacancies, which are difficult to control at the atomic level. In particular, the controlled production of vacancies has been so far elusive.

In this study, we present a remote plasma whereby the energetic species, particularly ions, are separated spatially from hBN, to controllably generate vacancies.[1] Properties of the remote plasma are characterized by Langmuir probe measurements and binary collision approximation simulations. Combined with atomic force microscopy (AFM) imaging of the hBN surface helps provide insight into structural changes resulting from ion bombardment. We then show by photoluminescence mapping and time-correlated photon counting that process conditions exist where damage is minimized but emitters are created without preference for structural imperfections (i.e., edges or folds). The results establish remote plasma processing for the fabrication of single photon emitters in ultrathin hBN, and show the importance of vacancy generation as another knob in addition to impurities for the tuning of emitter properties.

1. Bhattacharya et al., Appl. Phys. Lett. 128, 214103 (2026).

9:15am **2D-WeM-6 Probing Static and Dynamical Phenomena in Magnetic Systems Using Spin Defects in Hexagonal Boron Nitride***, **Kartik Shah**, Pratyush Saud,* Carnegie Mellon University*; Anshuman Sahoo, Ravi Kumar Bandapelli, Raghvendra Posti, I-Hsuan Kao,* Carnegie Mellon University, USA*; James Edgar,* Kansas State University*; Jyoti Katoch, Simranjeet Singh,* Carnegie Mellon University, USA

Atomic vacancies in van der Waal materials, like hexagonal Boron Nitride (hBN), have emerged as a versatile quantum sensing platform. The exceptional ease of integration of hBN based quantum sensors with various 2D systems has proven to be of substantial importance as a quantum probe. In this work, we will present the characterization techniques for the establishing properties of optically active spin defects in hBN. We employ Photoluminescence (PL) spectroscopy and PL mapping to probe the defect ensemble and lateral uniformity of the defect centres in hBN. As a primary application of these defects as quantum sensors, we explore its utility to study magnetism in a van der Waals (vdW) ferromagnet, particularly $Fe_XGa_YTe_2$, at room temperature. By integrating ion flux irradiated hBN flakes (containing spin defects) with vdW magnetic layer, via a dry transfer method, we probe spatially resolved spin phenomena in the ferromagnet layer at a microscopic level. Our work will establish the utility of hBN based sensors to probe spin related interactions/phenomena in vdW-based systems with high spatial resolution, thus providing a robust framework for probing emergent magnetism in low-dimensional systems.

9:30am **2D-WeM-7 Characterization of Optically Active Spin Defects in hBN as Quantum Sensors**, ***Pratyush Saud**, Anshuman Sahoo, Kartik Shah,* Carnegie Mellon University, USA*; I-Hsuan Kao,* Taiwan Semiconductor Manufacturing Company*; Raghvendra Posti, Ravi Kumar Bandapelli,* Carnegie Mellon University, USA*; James H. Edgar,* Kansas State University*; Jyoti Katoch, Simranjeet Singh,* Carnegie Mellon University, USA

Abstract:

Quantum sensing employing optically active spin defects in hexagonal boron nitride (hBN), specifically the negatively charged boron vacancy (V^-_B), has shown a capacity to investigate local spin dynamics[1]. Building upon the initial principles established by V^-_B-based sensing platforms, our work aims at expanding capabilities of 2D-based material characterization by moving toward more stable and spin-active carbon-related defects in hBN, as well as defects generated through neutron irradiation. Carbon-related defects possess optical and spin characteristics that make them suitable for precise spin manipulation and improved quantum sensing[2]. In this study, we present comprehensive time-resolved measurements of these defects to evaluate their potential as sensors for probing static and dynamical phenomena in magnetic systems. Through the driving of Rabi oscillations and the determination of longitudinal spin-lattice relaxation (T_1) times, the study characterizes the coherence limits and manipulation fidelity of these centers. These time-resolved protocols demonstrate the benefits of carbon-related centers compared to standard V^-_B ensembles for investigating weak, spatially localized magnetic fields. This optimized quantum sensing architecture is intended to address the metrological limitations of 2D-based systems' characterization, providing a sensitive platform for the discovery of new physical phenomena and the direct observation of spin interactions in emergent 2D magnetic materials.

References:

[1] Shekhar Das, Alex L. Melendez, I-Hsuan Kao, Janeth A. Garcia-Monge, Daniel Russell, Jiahan Li, Kenji Watanabe, Takashi Taniguchi, James H. Edgar, Jyoti Katoch, Fengyuan Yang, P. Chris Hammel, and Simranjeet Singh. Quantum sensing of spin dynamics using boron-vacancy centers in hexagonal boron nitride. Phys. Rev. Lett., 133:166704, Oct 2024

[2] Xingyu Gao, Sumukh Vaidya, Kejun Li, Zhun Ge, Saakshi Dikshit, Shimin Zhang, Peng Ju, Kunhong Shen, Yuanbin Jin, Yuan Ping, and Tongcang Li. Single nuclear spin detection and control in a van der waals material. Nature, 643:943–949, 2025.

9:45am **2D-WeM-8 Towards Probing spin dynamics in mesoscopic sized 2D magnets**, ***Anshuman Sahoo**, Pratyush Saud, I-Hsuan Kao, Raghvendra Posti,* Carnegie Mellon University*; Kartik Shah,* carnegie Mellon University*; Ravi Kumar Bandapelli,* Carnegie Mellon University*; Bing Lv,* University of Texas at Dallas*; Jyoti Katoch,* Carnegie Mellon University*; Simranjeet Singh,* carnegie Mellon University

Absttrat:

van der Waals (vdW) based antiferromagnets (AFMs) are an emerging class of materials, which can enable high density and ultrafast magnetic memory technologies. The spin dynamics in conventional AFMs is not well studied because magnetic resonance frequency often lies in the terahertz regime, which is not easy to access in research labs. However, vdW based materials that exhibit weak interlayer coupling, resonance frequency is in the gigahertz regime, and yet existing studies (using conventional techniques) are mainly limited to bulk crystals [1][2]. The understanding of spin dynamics in AFMs in the 2D atomic limit is needed for envisoned devices but it remains critically missing. A long-standing challenge has been the requirement of ultra-high-sensitive technique to probe spin dynamics in exfoliated flakes of 2D materials. Here, we present our work on developing a new technique for the broadband detection of spin dynamics in mesoscopic sized samples of 2D materials at cryogenic temperatures. We employ microwave interferometry to enhance the signal to noise ratio (SNR) [3], thus enabling the detection of spin dynamics in mesoscopic sized 2D materials. We will present the results of antiferromagnetic resonance experiments performed on CrSBr, which is layered A-type AFM. Our interferometer provides a versatile platform for studying the magnetic properties, i.e. magnetic damping, interlayer coupling, and anisotropy effects in low-dimensional systems.

References:

1] D. MacNeill, J. T. Hou, D. R. Klein, P. Zhang, P. Jarillo-Herrero, and L. Liu. Gigahertz frequency antiferromagnetic resonance and strong magnon-magnon coupling in the layered crystal crcl3. Physical Review Letters, 123(4):047204, 2019.

[2] T. M. J. Cham, S. Karimeddiny, A. H. Dismukes, X. Roy, D. C. Ralph, and Y. K. Luo.Micrometer-scale magnetic resonance imaging of two-dimensional ferromagnets. NanoLetters, 22(16):6716–6721, 2022.

[3] S. Tamaru, K. Yakushiji, A. Fukushima, S. Yuasa, and H. Kubota. Highly sensitive ferromagnetic resonance detection using a microwave interferometer. IEEE Magnetics Letters, 5:3700304, 2014.

11:00am **2D-WeM-13 A New Topological Monolayer**, ***Qiong Ma**,* Boston College **INVITED**

I will present experimental studies of the topological and correlated electronic properties of monolayer TaIrTe4. I first discuss the realization of a *dual quantum spin Hall (QSH) insulator* arising from the interplay between single-particle band topology and density-tuned electronic correlations. At charge neutrality, monolayer TaIrTe4 exhibits QSH behavior, characterized by enhanced nonlocal transport and quantized helical edge conduction. Upon electron doping, the system briefly becomes metallic before entering a correlated insulating state, likely driven by an electronic instability near conduction-band van Hove singularities, such as a charge density wave. Remarkably, within this correlated gap, the QSH state re-emerges. I will then report the discovery of a *nonvolatile superlattice memory effect* in the same material. In a pristine monolayer, we observe the spontaneous formation of a long-period superlattice that can be reversibly programmed ON and OFF via electrostatic tuning of low-energy electronic states. This switching toggles between two lattice configurations with unit-cell areas differing by nearly two orders of magnitude. Our results reveal two distinct but coupled instabilities—one electronic and one structural—enabling electrostatic control of lattice configurations with nonvolatile memory. These findings are established through a combination of nonlinear Hall measurements that probe quantum geometry and Raman spectroscopy that tracks lattice reconstruction.

11:30am **2D-WeM-15 Spatially-resolved Voltage-reversal due to Bernoulli Potentials in Dissipative Bi2Sr2CaCu2O8+x**, ***Sharadh Jois**, Gregory M. Stephen, Samuel W. LaGasse,* Laboratory for Physical Sciences*; Genda Gu,* Brookhaven National Laboratory*; Aubrey T. Hanbicki, Adam L. Friedman,* Laboratory for Physical Sciences

We measure magneto-transport and critical currents in $Bi_2Sr_2CaCu_2O_{8+x}$ Hall bar devices. Above critical current in an applied magnetic field, we observe longitudinal differential voltage along one edge comparable in magnitude but opposite in sign to the other edge. This phenomenon is unaffected by reversal of the applied field, and seems unique to devices with invasive voltage contacts. We attribute the source of this behavior to particle-hole symmetry breaking in moving vortices and the formation of opposite Bernoulli potentials due to opposing vortex velocities at the edges where the invasive contacts create hotspots for rapid vortex nucleation and flux flow. These results are fundamental to the composition and flow of dissipative currents in layered superconductors.

https://arxiv.org/abs/2604.19467

11:45am **2D-WeM-16 Signature of Ferromagnetic and Ferroelectric Coupling in WTe₂/Cr2Ge2Te6 Heterostructures**, ***Zhenhong Cui**, Ravi Kumar, I-Hsuan Kao, Raghvendra Posti, Jyoti Katoch, Simranjeet Singh,* Carnegie Mellon University

Electric-field control of magnetism is a central goal in multiferroic and spintronic devices, where ferroelectric polarization can be used to tune the magnetic states without a global magnetic field or large writing current. Van der Waals heterostructures provide a flexible platform for exploring this coupling by stacking a ferroelectric layer with a ferromagnetic layer. In this work, we study a dual-gated bilayer heterostructure, combining gate-switchable ferroelectric weyl semimetal WTe_2 and the ferromagnetic semiconductor $Cr_2Ge_2Te_6$ (CGT). The bilayer WTe_2 exhibits ferroelectric hysteresis in longitudinal resistance under electric field switching. Since WTe_2 can also generate a current-induced spin polarization with an out-of-plane component due to the low-symmetry crystal structure, this allows us to used unconventional unidirection magnetoresistance, which is sensitive to both spin-polarization and magnetization, as an electrical readout for the out-of-plane magnetization of CGT. Given the advantage of dual-gated geometry, the carrier density and displacement field can be independently tuned in the heterostructure, and we show that the UMR amplitude is strongly modulated by electrostatic gating. In addition, the displacement-field-dependent UMR response follows the ferroelectric hysteresis in bilayer WTe_2, suggesting that ferroelectric switching can modulate the spin-dependent magnetotransport response of the WTe_2/CGT heterostructure.

These results suggest bilayer WTe_2/CGT as a possible platform for studying ferroelectric and ferromagnetic coupling and gate-tunable spin polarization in van der Waals devices.

12:00pm **2D-WeM-17 Electrical Detection of NéEl Vector Reversal in a Van Der Waals Antiferromagnet***, **Raghvendra Posti**, Ravi Kumar Bandepalli,* Carnegie Mellon University*; Wenhao Liu,* The University of Texas at Dallas*; Anshuman Sahoo, Pratyush Saud,* Carnegie Mellon University*; Zixin Zhai,* The University of Texas at Dallas*; Zhenhong Cui, I-Hsuan Kao, Aalok Tiwari,* Carnegie Mellon University*; Thomas Poirier, James H. Edgar,* Kansas State University*; Kenji Watanabe, Takashi Taniguchi,* National Institute for Materials Science, Japan*; Bing Lv,* The University of Texas at Dallas*; Jyoti Katoch, Simranjeet Singh,* Carnegie Mellon University

Antiferromagnets (AFMs) are a promising platform for next-generation spintronic and magnonic technologies owing to their intrinsic ultrafast spin dynamics, absence of stray magnetic fields, and robustness against external perturbations. In particular, electrical control and detection of the Néel vector, the fundamental order parameter of AFMs, is central to realizing ultrafast magnetic memory devices. Recent discoveries of two-dimensional van der Waals AFMs have provided a versatile material platform for exploring antiferromagnetic spin transport and dynamics, where reduced dimensionality and weak interlayer exchange coupling enable access to different magnetic phases at relatively low magnetic fields. Despite these advances, electrical detection of complete 180° reversal of the Néel vector remains a major challenge due to the absence of net magnetization in antiferromagnets. Here, we focus on the layered A-type antiferromagnet CrSBr, which exhibits highly spin-dependent transport arising from its spin-polarized electronic structure. Utilizing this spin-dependent transport, we probe the Néel-vector orientation in CrSBr through tunnel magnetoresistance between CrSBr and a ferromagnetic spin-polarized electrode. To realize this, we fabricate Co/hBN/CrSBr tunnel junctions and perform magnetotransport measurements. We demonstrate that spin-dependent tunnelling between Co and CrSBr enables electrical detection of the Néel vector and its 180° reversal. Furthermore, this detection scheme is robust for both even- and odd-layer CrSBr devices and remains observable up to Néel transition temperature of CrSBr.

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