

PCSI

Room Ballroom South - Session PCSI-MoE

2D Materials Characterization and Devices

Moderator: Ursula Wurstbauer, University of Münster

7:45pm **PCSI-MoE-1 Determining Chirality of Non-Centrosymmetric FeGe and MnGe with Spin-polarized Imaging of MnGe Spin Spirals via STM, J. P. Corbett, J Repicky, T Zhu, A Ahmed, R Bennet**, The Ohio State University; *J Guerrero-Sanchez*, Universidad Nacional Autonoma de Mexico, Mexico; *R Kawakami*, Ohio State University-Columbus; *J Gupta*, The Ohio State University

Recent interest in the 'B20' phase of FeGe and MnGe stems from noncollinear magnetic states, such as magnetic Skyrmions[1]. Here we present a joint STM and DFT study of FeGe and MnGe films grown by molecular beam epitaxy. An average surface lattice constant of ~ 6.8 Å (FeGe) and of ~ 6.9 Å (MnGe), in agreement with the bulk values, was observed via and LEED, as well as in situ RHEED during the MBE growth. Atomic resolution images of each of the four possible chemical terminations in the FeGe films were characterized by distinct image contrast and corrugation, as well as local density of states in tunneling spectra [2]. Likewise, three of the four possible chemical terminations of MnGe were identified in atomic resolution STM images. These assignments were confirmed by the good agreement between the STM images and DFT-simulated images using the Tersoff-Haman approximation. Having determined the surface terminations, STM images of the atomic layering order and registry across step edges allows us to uniquely determine the stacking order, and hence chirality of these films, which is difficult with conventional crystallography techniques.

The noncollinear spin state of MnGe stems from 3 interacting spin spirals, the triple- \mathbf{q} state[1]. We have imaged spin-spirals of MnGe by SP-STM whose structure persists across quad-layer atomic steps which necessarily have the same surface termination. In contrast, the observed spiral contrast changes direction across non-quad-layer steps between different surface terminations. Spin-polarized tunneling spectroscopy reveals a pronounced field-dependence on one of these terminations, which is in good agreement with the calculated spin-resolved partial densities of states from DFT. These studies lay the groundwork for tuning Skyrmion size and thermal stability in B20-based interfacial heterostructures [1]

[1] Kanazawa, N., et al. Phys. Rev. B **96**, (2017): 220414

[2] Corbett, J. P., et al. arXiv:1807.00741

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8:00pm **PCSI-MoE-4 Ultrafast Spin and Charge Transfer in Monolayer WSe₂-Graphene Heterostructure Devices, Michael Newburger, K Luo**, Ohio State University-Columbus; *K McCreary*, Naval Research Laboratory; *I Martin*, *E McCormick*, Ohio State University-Columbus; *B Jonker*, Naval Research Laboratory; *R Kawakami*, Ohio State University-Columbus

Monolayer transition metal dichalcogenides (TMDs) such as WSe₂ have garnered much attention due to their long spin/valley lifetimes and ability to optically excite spin/valley polarization. Additionally, one of the great strengths of TMDs is their ability to compliment other materials, such as graphene, by acting as a means of optical spin injection or proximity coupling. Recently multiple groups have observed efficient, proximity mediated charge transfer in TMD/graphene heterostructures [1]. Moreover, magnetoresistance measurements have demonstrated the ability to optically inject spins from TMD to graphene [2]. However, little work has been done to quantify the speed of spin transfer across a TMD/graphene interface or its effect on spin/valley lifetime.

Here we use time-resolved Kerr rotation (TRKR) microscopy to image the spatial dependence of spin/valley dynamics in monolayer WSe₂/graphene heterostructures. Under p-type gating, Kerr rotation spatial maps of bare CVD grown WSe₂ demonstrate a characteristically spatial dependent, long-lived spin/valley signal [3]. Surprisingly though, these Kerr maps show strong quenching of spin/valley density at the WSe₂/graphene interfaces. Time delay scans of the interfaces reveal lifetimes as low as several picoseconds, up to 3 orders of magnitude lower than typical lifetimes in bare WSe₂. In addition, photoluminescence maps show quenched emission at the interfaces, whereas photoconductivity is enhanced at the same locations, demonstrating efficient charge transfer from WSe₂ to graphene. From these results, we conclude that the ultrafast quenching of spin/valley lifetime is due to transfer of spin information by the efficiently conducted charge carriers.

[1] B. Yang, E. Molina, J. Kim, D. Barroso, M. Lohmann, Y. Liu, Y. Xu, R. Wu, L. Bartels, K. Watanabe, T. Taniguchi, and J. Shi *Nano Letters* **18** (6), 3580-3585 (2018)

[2] Y. K. Luo, J. Xu, T. Zhu, G. Wu, E. J. McCormick, W. Zhan, M. R. Neupane and R. K. Kawakami. *Nano Lett.* **17**(6), 3877-3883(2017).

[3] E. J. McCormick, M. J. Newburger, Y. K. Luo, K. M. McCreary, S. Singh, I. B. Martin, E. J. Cichewicz, B. T. Jonker and R. K. Kawakami. *2D Mater.* **5** 11010 (2017)

8:05pm **PCSI-MoE-5 Probing Quantum Hall and Quantum Valley Hall Effect in Bilayer Graphene Nanostructures, Jing Li**, Los Alamos National Laboratory; *J Zhu*, The Pennsylvania State University

The lowest $N = 0$ and 1 Landau levels (LLs) in bilayer graphene carry particularly rich physics due to the eight-fold degeneracy resulting from the spin, orbital isospin and valley degree of freedom. External knobs such as perpendicular electric field and tilted magnetic field put the ordering of electronic degree of freedom in bilayer graphene into a competitive fashion, which leads to a rich variety of many-body ground states such as postulated canted anti-ferromagnet, and a quantum spin Hall liquid have been observed. However, a general LL diagram in this system is still missing. We parameterize all the interaction effects and demonstrate an effective single-particle LL diagram for the quantum Hall (QH) octet in bilayer graphene in the presence of an electric field [1], which provides a framework to interpret a diverse group of experimental findings in the literature. This could serve as a starting point to explore more sophisticated effects of electron-electron interactions. Moreover, we demonstrate gate-controlled tunneling of QH edge states between two lateral QH systems in bilayer graphene by using a pair of dual split gates [2], which allow us to independently control the filling factors of the QH systems and also the potential profile in the tunnel junction. We observe sequential pinch-off of individual edge states, and the potential profile in the junction can be well understood using finite element simulations. The gate-controlled transmission of edge states is the foundation towards realizing more sophisticated nanostructures which enable further exploration of the intriguing fractional QH states in bilayer graphene.

In a separate project, we have demonstrated the existence of theory predicted valley-momentum locked edge states, i.e. quantum valley Hall (QVH) kink states, in a line junction of two oppositely gated bilayer graphene [3]. More recently, we have obtained ballistic QVH kink states with quantized conductance of $4e^2/h$, and furthermore valleytronic operations such as valley valve and electron beam splitter have been realized using these high quality kink states [4]. The versatile controls and potential scalability of this new helical 1D system open a door to many exciting possibilities in low dimensional topological applications.

[1] J. Li et al, Phys. Rev. Lett. **120**, 047701 (2018)

[2] J. Li et al, Phys. Rev. Lett. **120**, 057701 (2018)

[3] J. Li et al, Nat. Nanotech. **11**, 1060-1065 (2016)

[4] J. Li et al, arXiv:1708.02311 (2017)

8:10pm **PCSI-MoE-6 Optoelectronic Modulation in 2D Mo_{1-x}W_xTe₂ Monolayers, Zakaria Al Balushi**, UC Berkeley

Alloys of transition metal dichalcogenides (TMDs), such as Mo_{1-x}W_xTe₂, exhibit a wide range of electronic properties (semiconducting, semimetal and metallic phases) with unique polymorphs that depend on atomic stacking and coordination. However, reversible tunability between such phases is challenging. This is largely due to a combination of differences in the free energy between TMD polymorphs and phase transition kinetic barriers. Phase modulation in MoTe₂ has, however, gained recent interest due to the low barrier for transition (40 meV) between its semiconducting and semimetal phases when compared to other TMDs. Evidently, dynamic control between the thermodynamically favorable semiconducting 2H phase and the metastable semimetal 1T' phase in MoTe₂ is achieved with a variety of external stimuli, including strain, temperature and electrostatic doping. In the latter case, theory predicts that this phase transition occurs when the charge density exceeds $\sim 10^{14}$ cm⁻², which has been experimentally verified in monolayer MoTe₂ using ionic gating. However, reversible switching between these phases with a solid-state electrostatic gate still remains elusive. To circumvent the charge density requirements, theory predicts that the barrier for phase transition can be reduced in MoTe₂ when alloyed with tungsten. Evidence of this was demonstrated by Zhang et al. (arXiv:1709.03835), where an all solid-state resistive random-access memory device fabricated with Mo_{1-x}W_xTe₂ showed reversible switching between high and low resistance states. In addition to changes in conductivity, another feature of the phase transition in MoTe₂ includes in-

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plane structural changes that should give rise to district optical anisotropic responses in monolayers which remains highly unexplored.

We investigate and compare changes in the optical response of 2H-MoTe₂ and 2H-Mo_{1-x}W_xTe₂ alloys as they undergo phase transition between semiconductor-to-semimetal phases in an all vdW device structure using an hBN gate dielectric and graphene contacts. The optical response of the vdW stack are investigated using angle- and polarization-dependent reflection measurements as a function of gate voltage. Initial results showed changes in the optical response of the vdW stack between (1.1–1.4μm) with applied gate voltage in alloys with x=0.09. Furthermore, polarization and temperature-dependent Raman measurements are also performed to map out structural changes in Mo_{1-x}W_xTe₂ as a function of applied gate voltage. These results will provide new insight into the optical response of these materials to enable new avenues for application in low-voltage and ultrafast modulators and other nanophotonic devices.

8:15pm PCSI-MoE-7 Pressure-controlled Photoluminescence and Identification of an Electronic State in Hydrated Methyl-Terminated Germanane, B.A. Noesges, T Asel, W Huey, S Jiang, K Krymowski, Y Wang, W Windl, J Goldberger, L Brillson, The Ohio State University

Two-dimensional (2D) materials continue to be an exciting area of research due to their interesting properties including large surface-to-volume ratio, high free carrier mobility and ease of stacking with other 2D materials to modular device design. Germanane, a germanium analogue to graphene, has a direct band gap around 1.6 eV that can be tuned by modifying the ligand termination on the Ge scaffold creating opportunity for optoelectronic applications [1]. Germanane, synthesized by deintercalating CaGe₂ with an acid chosen for a desired ligand termination, is sensitive to many factors which impact the behavior of this material. Defects in the Ge scaffold and incomplete reactions can create electronically active states within the band gap [2]. External factors such as ambient pressure and contaminants sitting between 2D layers can also play a large role in the observed electronic properties. We used an atmosphere-controlled photoluminescence spectroscopy (PLS) setup combined with depth-resolved cathodoluminescence spectroscopy (DRCLS) and density functional theory (DFT) calculations to investigate how atmospheric conditions affect germanane. Both pressure and atmospheric composition effects were seen. First, we observed the intensity of the photoluminescence measurement of germane vanish above a few hundred millitorr. Our original PLS measurements taken in low vacuum agree well with DRCLS collected in ultra-high vacuum (UHV) conditions [2]. If the germanane is in a water-free gas such as N₂, O₂, or Ar atmosphere, the luminescence stays quenched and no further states develop. However, once H₂O is introduced either by simply using ambient air or bubbling a gas through water, a new hydrated state emerges with higher than band gap energy photons emitted at 1.8-1.9 eV which can be removed upon returning the germanane to vacuum. This demonstrates pressure-reversible control of the germanane electronic structure with atmospheric conditions. This work supported by NSF MRSEC under award number DMR-1420451.

[1] S. Jiang, K. Krymowski, T. Asel, M.Q. Arguilla, N.D. Cultura, E. Yanchenko, X. Yang, L.J. Brillson, W. Windl, J.E. Goldberger, Chem. Mater. 28, 8071-8077 (2016).

[2] T.J. Asel, E. Yanchenko, X. Yang, Shishi Jiang, Kevin Krymowski, Y. Wang, A. Trout, D.W. McComb, W. Windl, J.E. Goldberger, L.J. Brillson, Appl. Phys. Lett. 113, 061110 (2018).

8:20pm PCSI-MoE-8 Ultrafast Hot Electron Dynamics in InAs Nanowires with Variable Crystal Phases Investigated by Time-resolved Photoelectron Emission Microscopy, L Wittenbecher, J Vogelsang, S Lehmann, K Thelander, D Zigmantas, Anders Mikkelsen, Lund University, Sweden

The III-V nanowire (NW) technology platform has reached a level of advancement that allows atomic scale tailoring as well as flexible device integration. In particular, controlled axial stacking of Wurtzite (Wz) and Zincblende (Zb) crystal phases is uniquely possible in the NWs[1]. We have previously found that multiphoton electron excitations can be controllably varied across the NW crystal segments [2] and that segments retain their unique electronic properties to the smallest possible scales[3]. In the present study we employ ultrafast time resolved PEEM utilizing femtosecond laser sources to explore the initial stages of the photo-carrier relaxation dynamics in InAs nanowires consisting of segments with different crystal structure. To this end, we combine PEEM with a tunable femtosecond laser source delivering sub 20fs pulses in the visible spectral range and perform spatially resolved one-color pump-probe measurements on individual nanowires. The photoelectron yield is found to increase

within approximately 100fs after excitation, followed by an exponential decay with a dominant time constant of about 400fs. We tentatively attribute these signals to the thermalization and the cooling of the photo-excited electrons. Furthermore, we demonstrate local variations of the relaxation times within individual nanowires as a function of excitation light polarization and crystal structure.

[1] D. Jacobsson et al, Nature, 531 (2016) 317

[2] J.V. Knutsson et al, ACS Nano, 11 (2017) 10519

[3] E. Mårzell et al, Nano Lett. 18 (2018) 907

8:25pm PCSI-MoE-9 Van der Waals Integration beyond 2D Materials, Xiangfeng Duan, UCLA

INVITED

The heterogeneous integration of dissimilar materials is a long pursuit of material science community and has defined the material foundation for modern electronics and optoelectronics. The current material integration strategy such as chemical epitaxial growth usually involves strong chemical bonds and is typically limited to materials with strict structure match and processing compatibility. Materials with substantially different lattice structures cannot be epitaxially grown together without generating too much interfacial defects that seriously alter/degrade their intrinsic properties. Alternatively, *van der Waals* integration, in which pre-formed building blocks are physically assembled together through weak *van der Waals* interactions, offers a bond-free material integration approach. The flexible “physical assembly” process used in *van der Waals* integration is not limited to materials that have similar lattice structures or require similar synthetic conditions. It can thus open up vast possibilities for damage-free integration of highly distinct materials beyond the traditional limits posed by lattice matching or process compatibility requirements, as exemplified by the recent blossom in the *van der Waals* integration of a broad range of 2D heterostructures. Here I will discuss *van der Waals* integration as a general material integration approach for creating diverse heterostructures with minimum integration-induced damage and interface states, enabling high-performing devices (including high speed transistors, diodes, flexible electronics) difficult to achieve with conventional “chemical integration” approach [1-10]. Recent highlights include the formation of *van der Waals* metal/semiconductor contacts free of Fermi level pinning to enable the first experimental validation of the Schottky-Mott rule since the initial prediction in 1930s [9]; and the development of *van der Waals* thin films for high performance large area electronics [10]; and the creation of a new class of *van der Waals* 2D-molecular superlattices with radically different layers yet atomic precision in each layer [7].

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[2] L. Liao, J. Bai, Y. Qu, Y. Lin, Y. Li, Y. Huang and X. Duan. Proc. Natl. Acad. Sci. 107, 6711-6715 (2010)

[3] L. Liao, Y. Lin, M. Bao, R. Cheng, J. Bai, Y. Liu, Y. Qu, K.L. Wang, Y. Huang and X. Duan. Nature 467, 305-308 (2010).

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[5] W. J. Yu, Z. Li, H. Zhou, Y. Chen, Y. Wang, Y. Huang and X. Duan. Nature Mater. 12, 246-252 (2013)

[6] R. Cheng, S. Jiang, Y. Chen, Y. Liu, N.O. Weiss, H.C. Cheng, H. Wu, Y. Huang and X. Duan. Nature Commun. 5, 5143 (2014)

[7] Y. Liu, N. O. Weiss, X. Duan, H. C. Cheng, Y. Huang and X. Duan. Nature Rev. Mater. 1, 16042 (2016).

[8] C. Wang, Q. He, U. Halim, Y. Liu, E. Zhu, Z. Lin, H. Xiao, X.D. Duan, Z. Feng, R. Cheng, N. Weiss, G. Ye, Y.C. Huang, H. Wu, H.-C. Cheng, L. Liao, X. Chen, W.A. Goddard, Y. Huang and X. Duan. Nature 555, 231-236 (2018).

[9] B. Yao, S.-W. Huang, Y. Liu, A. K. Vinod, C. Choi, M. Hoff, Y. Li, M. Yu, Z. Feng, D.-L. Kwong, Y. Huang, Y. Rao, X. Duan and C. W. Wong. Nature 558, 410-414 (2018).

[10] Y. Liu, J. Guo, E. Zhu, L. Liao, S. Lee, M. Ding, I. Shakir, V. Gambin, Y. Huang and X. Duan. Nature 557, 696-700 (2018).

[11] Z. Lin, Y. Liu, U. Halim, M. Ding, Y. Liu, Y. Wang, C. Jia, P. Chen, X. Duan, C. Wang, F. Song, M. Li, C. Wan, Y. Huang and X. Duan. Nature (2018) (DOI: 10.1038/s41586-018-0574-4).

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