Next Generation Devices (NGDev)

External User Publications (NGDev)

T. Wang, Y. Zhu, **Z. Mao**, Y.-Q. Xu, "Tunneling Effects in Crossed $Ta_2Pt_3Se_8$-$Ta_2Pd_3Se_8$ Nanowire Junctions: Implications for Anisotropic Photodetectors," *ACS Applied Nano Materials* 4 (2), 1817-1824 (2021). 10.1021/acsanm.0c03223.

This work demonstrated nanoscale crossed p-n junctions formed by nanowires of two quasi-1D van der Waals (vdW) materials, i.e. p-type $Ta_2Pd_3Se_8$ (TPdS) and n-type $Ta_2Pt_3Se_8$ (TPtS). Such p-n junctions exhibit asymmetric nonlinear output behaviors, inelastic tunneling effects, and isotropic photocurrent signals. This study not only offers a way to build nanoscale junctions but also provides fundamental understandings of the electronic and optoelectronic properties of vdW nanowires and their heterojunctions. TPdS and TPtS single crystals used in this were synthesized using non-MIP CVT faculty equipment.

- External User S0049

S.S. Jo, A. Singh, L. Yang, S.C. Tiwari, S. Hong, A. Krishnamoorthy, M.G. Sales, S.M. Oliver, J. Fox, R.L. Cavalero, **D.W. Snyder**, P.M. Vora, S.J. McDonnell, P. Vashishta, R.K. Kalia, A. Nakano, R. Jaramillo, "Growth Kinetics and Atomistic Mechanisms of Native Oxidation of ZrS_xSe_{2-x} and MoS_2 Crystals," *Nano Letters* 20 (12), 8592-8599 (2020). 10.1021/acs.nanolett.0c03263.

Quantifying and understanding the oxidation mechanisms in the 2DCC-grown ZrS_xSe_{2-x} alloy series is particularly useful for processing electronic devices from Zr-based TMD. In this study, we provide insight and quantitative guidance for designing and processing semiconductor devices.

- External User Project Collaboration between R0014 and R0016

K. Xiong, X. Zhang, L. Li, F. Zhang, B. Davis, A. Madjar, A. Göritz, M. Wiestruck, M. Kaynak, N.C. Strandwitz, **M. Terrones**, **J.M. Redwing**, J.C.M. Hwang, "Temperature-dependent RF Characteristics of Al_2O_3-passivated WSe_2 MOSFETs," *IEEE Electron Device Letters* (2020) in press. 10.1109/LED.2020.2999906.

High-frequency characteristics of WSe_2 MOSFETs were studied as a function of temperature to assess device performance. WSe_2 samples provided by 2DCC were used in this study

- External User Project S0009 (non-R1)

J.J. Fox, S. Bachu, R.L. Cavalero, R.M. Lavelle, S.M. Oliver, S. Yee, P.M. Vora, **N. Alem**, **D.W. Snyder**, "Chemical Vapor Transport Synthesis, Characterization and Compositional Tuning of ZrS_xSe_{2-x} for Optoelectronic Applications," *Journal of Crystal Growth*, 542, 125609 (2020). 10.1016/j.jcrysgro.2020.125609.

The high anisotropy of the 1T phase of $ZrSe_2$ and ZrS_2 gives rise to a high absorption coefficient which is of interest for photovoltaics and photodetectors. This study explored the CVT synthesis and optical properties of the $Zr(S,Se)_2$ alloy bulk crystals, synthesized in the 2DCC Bulk Growth facility, over the entire composition range.

- External User Project R0016

K. Xiong, M. Hilse, L. Li, A. Göritz, M. Lisker, M. Wietstruck, M. Kaynak, **R. Engel-Herbert**, A. Madjar, J.C.M. Hwang, "Large-Scale Fabrication of Submicrometer-Gate-Length MOSFETs

With a Trilayer $PtSe_2$ Channel Grown by Molecular Beam Epitaxy," *IEEE Transactions on Electron Devices*, 67 (3), 796-801 (2020). 10.1109/TED.2020.2966434

Successful integration of $PtSe_2$ (synthesized in the 2DCC Thin Films facility) as a new channel material into field effect transistor geometry and analysis of device characteristics.

- External User Project R0026 (non-R1)

J. Zhang, M. Boora, T. Kaminski, C. Kendrick, Y.K. Yapa, J.Y. Suh, "Fano resonances from plasmon-exciton coupling in hetero-bilayer WSe_2-WS_2 on Au nanorod arrays," *Photonics and Nanostructures – Fundamentals and Applications*, 100783 (2020). 10.1016/j.photonics.2020.100783.

Plasmon-exciton coupling was studied in WSe_2/WS_2 bilayers (synthesized in the 2DCC Thin Films facility) that were integrated with patterned Au nanorod arrays.

- External User Project S0040 (User from Non-R1).

J.J. Fonseca, A.L. Yeats, B. Blue, M.K. Zalalutdinov, T. Brintlinger, B.S. Simpkins, D.C. Ratchford, J.C. Culbertson, J.Q. Grim, S.G. Carter, M. Ishigami, R.M. Stroud, C.D. Cress, J.T. Robinson, "Enabling remote quantum emission in 2D semiconductors via porous metallic networks," *Nature Communications*, 11, 5, (2020). 10.1038/s41467-019-13857-0.

Demonstration of how two-dimensional crystal overlayers influence the recrystallization of relatively thick metal films and the subsequent synergetic benefits this provides for coupling surface plasmon-polaritons (SPPs) to photon emission in 2D semiconductors. TMD samples were grown in the 2DCC facility.

- External User Project R0024 (Government Lab User)

Z. Wu, J. Li, X. Zhang, **J.M. Redwing**, Y. Zheng "Room-Temperature Active Modulation of Valley Dynamics in a Monolayer Semiconductor through Chiral Purcell Effects," *Advanced Materials*, 1904132, (2019). 10.1002/adma.201904132

Demonstration of tunable and active modulation of valley dynamics in a monolayer WSe_2 (synthesized in 2DCC Thin Films facility) at room temperature through controllable chiral Purcell effects in plasmonic chiral metamaterials.

- External User Project S0064

D.R. Hickey, J.G. Azadani, **A.R. Richardella**, J.C. Kally, J.S. Lee, H.C. Chang, T. Liu, M.Z. Wu, **N. Samarth,** T. Low, K. A. Mkhoyan, "Structure and basal twinning of the topological insulator Bi_2Se_3 grown by MBE onto crystalline $Y_3Fe_5O_{12}$," *Physical Review Materials* [Rapid Communications] 3, 061201(R) (2019). 10.1103/PhysRevMaterials.3.061201

Detailed microscopy study of types of disorder present in topological insulator films grown on YIG using atomic force microscopy and scanning transmission electron microscopy, revealing the presence of an amorphous metal oxide layer between the substrate and the film, which appears to smooth out the nanometer-scale undulations in a YIG surface. Using density functional theory, the study explores the impact of observed basal twins on the electronic structure of TI films.

- External User Project S0025

W. Wu, C.K. Dass, J.R. Hendrickson, R.D. Montano, X. Zhang, **T.H. Choudhury**, **J.M. Redwing** and M.T. Pettes, "Locally defined quantum emission from epitaxial few-layer WSe_2," *Appl. Phys. Lett*. (2019). 10.1063/1.5091779

Demonstration of quantum emission from strain-localized WSe_2 epitaxial films that were grown in the 2DCC Thin Films facility.

- External User Project S0007

X. Ge, M. Minkov, **T. Choudhury**, **M. Chubarov**, S. Fan, **J. Redwing**, X. Li, W. Zhou, "Room Temperature Photonic Crystal Surface Emitting Laser with Synthesized Monolayer Tungsten Disulfide," *IEEE International Semiconductor Laser Conference*, 167-168 (2018). 10.1109/ISLC.2018.8516219

Demonstration of lasing with a narrow linewidth from WS_2 epitaxial monolayers grown in 2DCC Thin Films facility and integrated into a silicon nitride photonic crystal cavity.

- External User Project S0010 (User from MSI).

J. Han, **A. Richardella**, S. S. Siddiqui, J. Finley, **N. Samarth**, and L. Liu, "Room Temperature Spin-orbit Torque Switching Induced by a Topological Insulator," Phys. Rev. Lett., 119, 077702 (2017). 10.1103/PhysRevLett.119.077702

This project used Bi_2Se_3 and $(Bi,Sb)_2Te_3$ grown in the 2DCC Thin Films facility to carry out the first room temperature demonstration of energy efficient current driven spin-orbit torque switching in topological insulator-ferrimagnet heterostructure spintronic devices.

- External User Project S0003

Local User Publications (NGDev)

A. Sebastian, R. Pendurthi, **T.H. Choudhury**, **J.M. Redwing**, *S. Das*, "Benchmarking monolayer MoS_2 and WS_2 field-effect transistors," *Nature Communications* 12, 693 (2021). 10.1038/s41467-020-20732-w.

This paper benchmarks device-to-device variation in field-effect transistors (FETs) based on wafer-scale monolayer MoS_2 and WS_2 grown by MIP equipment MOCVD1 in the 2DCC facility. Statistical measures were used to evaluate key FET performance indicators for several hundred 2D FETs and were compared against existing literature as well as ultra-thin body Si FETs. Our results show consistent performance of the 2D FETs owing to high quality uniform layers and clean transfer onto device substrates. We demonstrate record high carrier mobility of 33 cm^2/Vs was measured in WS_2 FETs, which is a 1.5X improvement compared to the best literature report. Our results confirm the technological viability of 2D FETs in future integrated circuits.

- Local User project S0084
- Also science driver Epi2DC

A. Dodda, A. Oberoi, A. Sebastian, **T.H. Choudhury**, **J.M. Redwing**, *S. Das*, "Stochastic resonance in MoS_2 photodetector," *Nature Communications* 11, 4406 (2020). 10.1038/s41467-020-18195-0.

An ultra-low-power sensor based on stochastic resonance phenomena was demonstrated in photodetectors fabricated using large-area MoS_2 monolayers synthesized in the 2DCC facility. Stochastic resonance enables the detection of weak signals within the noise limit of the system and mimics the sensory information processing abilities of animals adapted to extreme and resource limited environments.

- Local User project S0084

D. Jayachandran, A. Oberoi, A. Sebastian, **T.H. Choudhury**, B. Shankar, **J.M. Redwing**, *S. Das*, "A low-power biomimetic collision detector based on an in-memory molybdenum disulfide photodetector," *Nature Electronics* (2020). 10.1038/s41928-020-00466-9.

A compact, low power nanoscale collision detector is demonstrated that mimics the lobula giant movement detector (LGMD) neuron in locusts which can detect an approaching object and prevent collisions within a swarm of millions of locusts. The biomimetic collision detector is comprised of molybdenum disulfide photodetectors stacked on top of a non-volatile and programmable floating-gate memory architecture. Large area MoS_2 monolayers synthesized in the 2DCC facility were used for photodetector fabrication.

- Local user project S0084

J.R. Rodriguez, W. Murray, K. Fujisawa, **S.H. Lee**, A.L. Kotrick, Y. Chen, N. McKee, S. Lee, **M. Terrones**, S. Trolier-McKinstry, T.J. Jackson, **Z. Mao**, Z. Liu and *Y. Liu*, "Electric field induced metallic behavior in thin crystals of ferroelectric alpha-In_2Se_3," *App. Phys. Lett.* 117 (5), 052901 (2020). 10.1063/5.0014945.

Field-effect transistors (FET), which use exfoliated nano flakes of ferroelectric semiconductor α-In_2Se_3 grown by the 2DCC bulk growth facility as the channel material were fabricated and tested. The transport measurements on these devices reveal evidence for the reorientation of electrical polarization and an electric field-induced metallic state in α-In_2Se_3. These results suggest the α-In_2Se_3 based FET devices can serve as a platform for the fundamental study of ferroelectric metals as well as the exploration of potential applications of semiconducting ferroelectrics.

- Local User Project S0039

A.D. Agyapong, K.A. Cooley, *S.E. Mohney*, "Reactivity of contact metals on monolayer WS_2," *Journal of Applied Physics* 128 (5), 055306 (2020). 10.1063/5.0014005.

A rapid non-destructive method based on Raman spectroscopy was developed to analyze the reactivity of contact metals with WS2 monolayers prepared in the 2DCC Thin Films facility. The metal/WS_2 reactivity observed in this study is in excellent agreement with predictions from bulk thermodynamics, which can provide good guidance for studies of other metal/TMD systems.

- Local User Project S0035

Q. Qian, L. Peng, N.P. Lopez, K. Fujisawa, K. Zhang, X. Zhang, **T.H. Choudhury**, **J. Redwing**, **M. Terrones**, X. Ma, *S. Huang*, "Defect creation in WSe_2 with microsecond photoluminescence lifetime by focused ion beam irradiation," *Nanoscale*, 12, 2047-2056 (2020). 10.1039/C9NR08390A

Focused ion beam was used to create defects in WSe_2 (bulk crystals and MOCVD monolayers synthesized in 2DCC Thin Films facility). Long photoluminescence lifetime was measured for defect-related emission peaks which is valuable for valleytronics, quantum emitters and other applications.

- Local User Project S0023

L. Ding, M.S. Ukhtary, **M. Chubarov**, **T.H. Choudhury**, F. Zhang, R. Yang, A. Zhang, J.A. Fan, **M. Terrones**, **J.M. Redwing**, T. Yang, M.D. Li, R. Saito, and *S.X. Huang*, "Understanding interlayer coupling in TMD-hBN heterostructures by Raman spectroscopy*," IEEE Trans. Electron. Dev.* 64(10), 4059-4067 (2018). 10.1109/TED.2018.2847230

Investigation and interpretation of interlayer interactions in 2D heterostructures grown in the 2DCC Thin Films facility by Raman spectroscopy.

- Local User Project S0023

In-house Research Publications (NGDev)

S. Novakov, B. Jariwala, N.M. Vu, A. Kozhakhmetov, **J.A. Robinson**, J.T. Heron, "Interface Transparency and Rashba Spin Torque Enhancement in WSe_2 Heterostructures," *ACS Applied Materials & Interfaces* 13 (11), 13744-13750 (2021). 10.1021/acsami.0c19266.

In this paper, enhanced spin transfer torques from the Rashba spin current in heterostructures of permalloy (Py) and WSe_2 is reported. The study shows that insertion of up to two monolayers of WSe_2 enhances the spin transfer torques in a Rashba system by up to 3×, without changing the fieldlike Rashba spin–orbit torque (SOT), a measure of interface polarization. The results indicate that low layer count TMD films can be used as an interfacial "scattering promoter" in heterostructure interfaces without quenching the original polarization. Materials in this study were provided by the 2DCC using non-MIP MOCVD faculty equipment.

- Also science driver Epi2DC

A. Woeppel, K. Xu, A. Kozhakhmetov, S. Wate, **J.A. Robinson**, S.K. Fullerton-Shirey, "Single- versus Dual-Ion Conductors for Electric Double Layer Gating: Finite Element Modeling and Hall-Effect Measurements," *ACS Applied Materials & Interfaces* (2020). 10.1021/acsami.0c08653.

Demonstration of how TMD transport can be electrostatically controlled using advanced polymer electrolytes. The project utilized non-MIP equipment as part of the Thin Film facility to create the 2D films, with contributions from in-house researchers.

- Also science driver AdvCM

M. Hilse, K. Wang, **R. Engel-Herbert**, "Growth of ultrathin Pt layers and selenization into $PtSe_2$ by molecular beam epitaxy," *2D Materials* 7 (4), 045013 (2020). 10.1088/2053-1583/ab9f91.

2D transition metal dichalcogenide system $PtSe_2$ was grown by MBE using in-situ post-deposition selenization to study layer crystallinity of this material system to be used as high mobility transistor channel materials for ultra-thin-body electronics.

N. Briggs, S. Subramanian, Z. Lin, X. Li, X. Zhang, K. Zhang, K. Xiao, D. Geohegan, R. Wallace, *L.-Q. Chen*, **M. Terrones**, *A. Ebrahimi*, S. Das, **J. Redwing**, C. Hinkle, K. Momeni, **A. van Duin**, **V. Crespi**, S. Kar, and **J.A. Robinson**, "A roadmap for electronic grade 2D materials," *2D Materials* 6 (2), 022001 (2019). 10.1088/2053-1583/aaf836

Review article highlighting applications, current status and future directions for the synthesis, processing and characterization of 2D layered chalcogenides with contributions from in-house researchers, local users and external users of 2DCC.

- Included external users from projects R0037 (User from Non-R1) and R0011

S. Subramanian, K. Xu, **Y. Wang**, S. Moser, N.A. Simonson, D. Deng, **V.H. Crespi**, S.K. Fullerton-Shirey, **J.A. Robinson**, "Tuning transport across MoS_2/graphene interfaces via as-grown lateral heterostructures," *npj 2D Materials and Applications*, 4, 9 (2020). 10.1038/s41699-020-0144-0.

Close coupling of theory and experiment here helps to accelerate the development of device applications for 2D materials through advancing the understanding of interfaces in lateral heterostructures that include transition metal dichalcogenides. The project utilized non-MIP equipment as part of the Thin Film facility to create the 2D films.

- Also science driver AdvCM

Z. Islam, A. Kozhakhmetov, **J. Robinson**, A. Haque, "Enhancement of WSe_2 FET Performance Using Low-Temperature Annealing," *Journal of Electronic Materials* (2020). 10.1007/s11664-020-08087-w.

In this study, we investigate a non-thermal annealing process for two-dimensional materials. Instead of high temperature, we exploit the electron wind force at near-room temperature conditions. The process is demonstrated on back-gated WSe_2 transistors. To explain the atomistic mechanisms behind the room-temperature annealing, we perform molecular dynamics simulation. The project utilized non-MIP equipment as part of the Thin Films facility to create the 2D films.

- Also science driver AdvCM

A. Kozhakhmetov, J.R. Nasr, F. Zhang, K. Xu, N.C. Briggs, R. Addou, R. Wallace, S. Sullerton-Shirey, **M. Terrones**, S. Das, **J.A. Robinson**, "Scalable BEOL compatible 2D tungsten diselenide," *2D Materials*, 7 (1), 15029, (2019). 10.1088/2053-1583/ab5ad1

Benchmark of carbon and alkali salt-free synthesis of fully coalesced, stoichiometric 2D WSe_2 films on amorphous SiO_2/Si substrates at BEOL- compatible temperatures (475 °C) via gas-source metal-organic chemical deposition. This work highlights the necessity of a Se-rich environment in a kinetically limited growth regime for successful integration of low-temperature 2D WSe_2. The project utilized non-MIP equipment as part of the Thin Films facility to create the 2D films.