

# Hybrid 2D Ferroic Heterostructures for Advanced Electronic Functionality

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## Hybrid 2D Ferroic Heterostructures for Advanced Electronic Functionality (FY20-23)

### SUMMARY

This program has been exceptionally productive, as evidenced by journal publications, patents, and a successful transition to a 6.1 external program at AFOSR. We have made significant progress in understanding the response of select 2D monolayer materials to ferroic stimuli, and in their controlled doping to better interface with ferroic materials. These achievements place NRL's research effort at the forefront of 2D material research worldwide, and have contributed to the expanding efforts in nanoscience and quantum materials.

Accomplishments include

- Ferroelectric modulation of quantum emitters in 2D materials
- Imprinting properties of ferroic a material onto adjacent 2D materials
- Establishing a baseline for response to ferroic stimuli: magnetic field response
- Modulating optical properties of 2D materials via ferroic interactions
- Mediating oxygen interlayer transport via a ferroic layer
- Controlled doping of 2D materials to better interface with ferroic materials
- demonstrated that ferroelectric (FE) polarization domains control the room temperature optical properties of an adjacent monolayer of 2D material

Details of each are provided below.

Productivity:

- 8 refereed journal publications (7 published, 1 under review)
- 10 patents either awarded or under review
- Transition to external AFOSR 6.1 program "Hybrid 2D/3D Ferroic Heterostructures for Advanced Electronic Functionalities"

### Technical Objectives

The goal is to use properties of a ferroic film, such as the very large ferroelectric (FE) surface charge density to control the optical, electronic and magnetic properties of an adjacent 2D film, and understand the fundamental mechanisms which mediate such effects. This is an entirely new and unexplored direction, and provides a unique and timely opportunity for original high-impact work with potential for significant payoff relevant to the Navy Framework Priorities "Integrated and Distributed Forces" and "Sensing and Sense-Making".

### Technical Approach

We will develop hybrid 2D ferroic heterostructures with new functionality relevant to the DoD mission by integrating transition metal dichalcogenide (TMD) monolayers with ferroic films such as ferroelectric (FE) films to control the optical, transport and magnetic properties of the TMD via interactions with the ferroic film. The FE polarization can be as high as 50-100  $\mu\text{C cm}^{-2}$ ,

corresponding to a surface charge density of  $\sim 5 \times 10^{14} \text{ cm}^{-2}$ , at least an order of magnitude higher than can be achieved in a conventional 2DEG system. It is in fact comparable to the surface atom density of a TMD material such as  $\text{MoS}_2$ , and thus offers one unit charge for every surface atom of the TMD monolayer. Therefore, we expect that such interface charge can readily control many properties of 2D materials, including the metal-insulator transition and charge-gated ferromagnetic order in select TMDs. We will initially focus on epitaxial lead zirconium titanate (PZT) films grown by sputter deposition in the NRL Epi-Center Facility due to their high surface charge. Accompanying control experiments on a TMD /  $\text{SrTiO}_3$  structure will utilize the continuously variable (but much smaller) photo-generated surface charge density in the  $\text{SrTiO}_3$  to determine the threshold charge density necessary to realize a particular effect. In a later phase of the project, we will utilize and develop the MOCVD synthesis of  $\text{In}_2\text{Se}_3$ , a new van der Waals FE material which will enable *in situ* fabrication of TMD / FE heterostructures such as  $\text{WSe}_2 / \text{In}_2\text{Se}_3$  or  $\text{In}_2\text{Se}_3 / \text{WSe}_2$  with pristine interfaces. This represents the ultimate scaling of such hybrid structures, and a "bottom up" approach towards design and fabrication of a new class of multi-functional, atomic-scale heterostructures with new properties.

### **Technical Progress by FY (in reverse chronological order)**

#### **FY23**

##### **Ferroelectric modulation of single photon emission in 2D materials**

Quantum photonics promises significant advances in secure communications, metrology, sensing and information processing/computation. Single photon sources are fundamental to this endeavor. However, the lack of high quality, scalable single photon sources remains a significant obstacle. We present here a new paradigm for the control of single photon emitters (SPEs) and single photon purity by integrating monolayer  $\text{WS}_2$  with the organic ferroelectric polymer poly(vinylidene fluoride-*co*-trifluoroethylene (P(VDF-TrFE))). Local strain fields produced by nanoindentation activate atomic scale defects within the two-dimensional  $\text{WS}_2$  to produce single photon emitters, whose intensity and purity are controlled by the polarization domains in the adjacent P(VDF-TrFE) film. Switching the ferroelectric polarization reversibly tunes the SPE purity between the classical and quantum light regimes, with single photon purities as high as 94%. This novel multidimensional heterostructure introduces a new avenue for control of quantum emitters by combining the nonvolatile ferroic properties of a ferroelectric with the radiative properties of the zero-dimensional atomic scale emitters embedded in the two-dimensional  $\text{WS}_2$  semiconductor monolayer.

Specifically, we demonstrate the nonvolatile and reversible control of single photon emission purity in monolayer tungsten disulfide ( $\text{WS}_2$ ) by integrating it with an organic ferroelectric polymer, poly(vinylidene fluoride-*co*-trifluoroethylene (P(VDF-TrFE))). We create an emitter in the  $\text{WS}_2$ , and are able to toggle the emission between high purity quantum light (characterized by sub-Poissonian statistics) and classical light (characterized by Poissonian statistics) by switching the ferroelectric polarization of the P(VDF-TrFE) with a bias voltage. We further demonstrate that the monolayer  $\text{WS}_2$  operates as a transparent top gate — application of a bias

voltage to the  $WS_2$  switches the ferroelectric polarization of the underlying P(VDF-TrFE) film. This approach enables nonvolatile modulation of the emission character by reversing the polarization of the ferroelectric domain under a given emitter, thereby switching between the quantum and classical regimes. This provides another avenue for encoding quantum photonic information, complementing more complex approaches such as spectral shearing. We achieve single photon emission purity  $P$  as high as 94%, as determined by the measured second order correlation function  $g^{(2)}(t=0)$  value of 0.06, where  $P = 1 - g^{(2)}(0)$ , the highest purity reported for  $WS_2$  SPEs to our knowledge. This novel heterostructure introduces a new paradigm for control of quantum emitters by combining the nonvolatile ferroic properties of a ferroelectric with the radiative properties of the zero-dimensional atomic scale emitters embedded in the two-dimensional  $WS_2$  semiconductor monolayer.

Refereed Publication: These results have been submitted for publication as “*Ferroelectric modulation of quantum emitters in monolayer  $WS_2$* ” by Sung-Joon Lee, Hsun-Jen Chuang, Andrew Yeats, Kathleen M. McCreary, Dante J. O’Hara, Berend T. Jonker (NRL/6305/JA--2023/3).

Patent: Ferroelectric modulation of quantum emitters in monolayer  $WS_2$ , Provisional patent 211878-US1 filed 30 Nov 2023.

### **Imprinting properties of ferroic material onto adjacent 2D materials**

The ability to assemble layers of two-dimensional (2D) materials to form permutations of van der Waals heterostructures provides significant opportunities in materials design and synthesis. Interlayer interactions provide a path to diverse properties and functionality, and understanding such interactions is essential to that end.

In this work, we grew few-layer  $Bi_2Se_3$  onto monolayer  $WS_2$ , and discovered that the lattice vibrational energies of the  $Bi_2Se_3$  were imprinted in a quantized manner onto the optical emission of the  $WS_2$ . We observed interlayer exciton-phonon coupling and formation of an exciton-phonon bound state between localized excitons in monolayer  $WS_2$  and the  $Bi_2Se_3$   $A_1^{(3)}$  surface phonon, a mode particularly susceptible to electron-phonon coupling. The bound state is manifested as a series of evenly spaced peaks superposed on the  $WS_2$  excitonic photoluminescence (PL) spectrum, whose periodic spacing corresponds to the  $A_1^{(3)}$  surface phonon energy. Oscillating features that match a phonon energy and correspond to a luminescence are indicative of electron-phonon or exciton-phonon bound states. In addition, polarized Raman spectroscopy of the  $Bi_2Se_3$  reveals multiple pronounced surface phonon modes and crystalline symmetry breaking. Notably, the presence of surface phonons in a forbidden scattering geometry suggests local symmetry breaking at the surface, consistent with a strong  $WS_2$ - $Bi_2Se_3$  interlayer coupling. Previous work found significant interlayer hybridization in  $Bi_2Se_3/WS_2$  heterostructures, facilitating electron transfer and modifying the bonding, conditions which encourage the formation of interlayer quasiparticles. Understanding the interlayer interaction is central to elucidating how their combined properties evolve, enabling the discovery of advanced capabilities for spintronics, valleytronics, and quantum computing applications.

Refereed Publication: Interlayer Exciton–Phonon Bound State in Bi<sub>2</sub>Se<sub>3</sub>/monolayer WS<sub>2</sub> van der Waals Heterostructures; Zachariah Hennighausen, Jisoo Moon, Kathleen M. McCreary, Connie H. Li, Olaf M. van't Erve and Berend T. Jonker. *ACS Nano* 17, 2529–2536 (January 2023). <https://doi.org/10.1021/acsnano.2c10313> ; NRL/6390/JA--2022/15

## FY22

### **Established a baseline for response to ferroic stimuli: magnetic field response**

Monolayer transition metal dichalcogenides host a variety of optically excited quasiparticles species that stem from two-dimensional confinement combined with relatively large carrier effective masses and reduced dielectric screening. The magnetic response of these quasiparticles gives information on their spin and valley configurations, nuanced carrier interactions, and insight into the underlying band structure. Recently, there have been several reports of 2s/3s charged excitons in TMDs, but very little is still known about their response to external magnetic fields. Using photoluminescence excitation spectroscopy, we observe the presence of the 2s charged exciton and report for the first time its response to an applied magnetic field. We benchmark this response against the neutral exciton and find that both the 2s neutral and charged excitons exhibit similar behavior with g-factors of  $g(X_o^{2s}) = -5.20 \pm 0.11$  and  $g(X^{-2s}) = -4.98 \pm 0.11$ , respectively. These results serve as a marker in mapping the behavior of the 2s charged state  $X^{2s}$  with magnetic field in TMDs. Experimental quantification of the g factor serves as another physical benchmark for future theoretical models of stable 2s charged states. Additionally, the stability of the X2s state offers a possible medium for studying the crossover from exciton Rydberg physics to the quantum Hall regime for charged species at high magnetic fields.

Refereed Publication: Magneto-Optical Measurements of the Negatively Charged 2s Exciton in WSe<sub>2</sub>, J.C. Sell, J.R. Vannucci, D.G. Suarez-Forero, B. Cao, D.W. Session, H.-J. Chuang, K.M. McCreary, M.R. Rosenberger, B.T. Jonker, S. Mittal, M. Hafezi; *Phys. Rev. B* 106, L081409 (2022) NRL/6390/JA--2022/1

### **Modulating optical properties of 2D materials via ferroic interactions**

We have demonstrated a way to tune the photoluminescence of a WS<sub>2</sub> monolayer adjacent to Bi<sub>2</sub>Se<sub>3</sub>. Characterizing and manipulating the circular polarization of light is central to numerous emerging technologies, including spintronics and quantum computing. Separately, monolayer tungsten disulfide (WS<sub>2</sub>) is a versatile material that has demonstrated promise in a variety of applications, including single photon emitters and valleytronics. Here, we demonstrate a method to tune the photoluminescence (PL) intensity (factor of x161), peak position (38.4meV range), circular polarization (39.4% range), and valley polarization of a Bi<sub>2</sub>Se<sub>3</sub>-WS<sub>2</sub> 2D heterostructure using a low-power laser (0.762μW) in ambient. Changes are spatially confined to the laser spot, enabling submicron (814nm) features, and are long-term stable (>334 days). The PL intensity and peak position changes can be controllably reversed through laser exposure

in vacuum, allowing the material to be erased and reused. Atmospheric experiments and first-principles calculations indicate oxygen diffusion modulates the exciton radiative vs. non-radiative recombination pathways, where oxygen absorption leads to brightening, and desorption to darkening.

Refereed Publication: Laser-Patterned Submicrometer  $\text{Bi}_2\text{Se}_3$ - $\text{WS}_2$  Pixels with Tunable Circular Polarization at Room Temperature. Hennighausen, Z.; Wickramaratne, D.; McCreary, K. M.; Hudak, B. M.; Brintlinger, T.; Chuang, H.-J.; Noyan, M. A.; Jonker, B. T.; Stroud, R. M.; van 't Erve, O. M. *ACS Appl. Mater. Interfaces* **2022**, *14* (7), 9504-9514. <https://doi.org/10.1021/acscami.1c24205>. NRL/6390/ON--2021/21

Patent Application: Navy Case 210154-US2

Patent Application: Navy Case 210154-US3

### **Mediating oxygen interlayer transport via a ferroic layer**

We utilized  $\text{Bi}_2\text{Se}_3$  as an oxygen transport layer to modulate the luminescence of an adjacent  $\text{WSe}_2$  monolayer. Oxygen conductors and transporters are important to several consequential renewable energy technologies, including fuel cells and syngas production. Separately, monolayer transition metal dichalcogenides (TMDs) have demonstrated significant promise for a range of applications, including quantum computing, advanced sensors, valleytronics, and next-gen optoelectronics. Here, we synthesize a few nanometer-thick  $\text{Bi}_x\text{O}_y\text{Se}_z$  compound that strongly resembles a rare  $R\bar{3}m$  bismuth oxide ( $\text{Bi}_2\text{O}_3$ ) phase, and combine it with monolayer  $\text{WSe}_2$ , which is highly sensitive to the environment. We use the resulting 2D heterostructure to study oxygen transport through  $\text{Bi}_x\text{O}_y\text{Se}_z$  into the interlayer region, whereby the 2D material properties are modulated, finding extraordinarily fast diffusion at room temperature under laser exposure. The oxygen diffusion enables reversible and precise modification of the 2D material properties by controllably intercalating and deintercalating oxygen. Changes are spatially confined, enabling submicron features (e.g. pixels), and are long-term stable for more than 221 days. Our work suggests few nanometer-thick  $\text{Bi}_x\text{O}_y\text{Se}_z$  is a promising unexplored room-temperature oxygen transporter. Additionally, our findings suggest the mechanism can be applied to other 2D materials as a generalized method to manipulate their properties with high precision and submicron spatial resolution.

Refereed Publication: Room-temperature oxygen transport in nano-thin  $\text{Bi}_x\text{O}_y\text{Se}_z$  enables precision modulation of 2D materials, Zachariah Hennighausen, Bethany M. Hudak, Madeleine Phillips, Jisoo Moon, Kathleen M. McCreary, Hsun-Jen Chuang, Matthew R. Rosenberger, Berend T. Jonker, Connie H. Li, Rhonda M. Stroud, and Olaf M. van 't Erve. *ACS Nano* *16*, 9, 13969–13981 (8 Sept 2022), <https://doi.org/10.1021/acsnano.2c03367>. NRL/6390/JA--2022/7

Patent Application: Navy Case 210973

### **Controlled doping of 2D materials to better interface with ferroic materials**

The development of processes to controllably dope two-dimensional semiconductors is critical to achieving next-generation electronic and optoelectronic devices. Understanding the nature of the contacts is a critical step for realizing efficient charge injection in transition metal dichalcogenides. In this study, post-growth n-doping of chemical vapor deposition grown monolayer (1L) WS<sub>2</sub> is achieved by treatment with solutions of molecular reductants. The extent of doping can be conveniently controlled by the concentration of dopant solutions and treatment time. Threshold voltage shifts and tunable channel current are observed in doped WS<sub>2</sub> field-effect transistors. This molecular n-doping technique is particularly useful for the selective area doping needed for electrical contacts and reduces the contact resistance ( $R_c$ ) in 1L WS<sub>2</sub> by more than two orders of magnitude. The significant reduction of  $R_c$  is attributed to the high electron-doping density achieved in WS<sub>2</sub>, which leads to a significant reduction of Schottky barrier height. The dependence of mobility on temperature shows clear evidence of the strong suppression of charge-impurity scattering after the doping. High levels of doping allow the observation of a metal-insulator transition in monolayer WS<sub>2</sub> due to strong electron-electron interactions. This doping technique provides a viable route to tailor the electrical properties and improve the contacts in transition metal dichalcogenides, paving the way for high-performance two-dimensional nanoelectronic devices.

Refereed Publication: Control of the Schottky Barrier Height in Single Layer WS<sub>2</sub> using Molecular Doping, Siyuan Zhang, Hsun- Jen Chuang, Son T. Le, Curt A. Richter, Kathleen M. McCreary, Berend T. Jonker, Angela R. Hight Walker, Christina A. Hacker\*, *AIP Advances* 12 (8), 085222 (August 2022). doi: 10.1063/5.0101033. NRL/6390/JA--2022/5

## **FY21**

FY21 was a very challenging year for experimental work, as the covid operating posture has severely restricted access to the extensive base of experimental equipment which forms the backbone of many NRL base programs. Although significant progress was made, as summarized below, it did not immediately culminate in the usual cluster of publications.

Our ferroelectric (FE) substrate of choice for this program was lead zirconium titanate (PZT) with an alloy concentration of PbZr<sub>0.2</sub>Ti<sub>0.8</sub>O<sub>3</sub>, because this material offered the highest surface charge density, corresponding to one electron (or hole) for every interface atom of the transition metal dichalcogenide (TMD) layer one deposited onto the surface. Our intent had been to develop sputter deposition of epitaxial PZT, since no commercial vendor offered the ultra-smooth films required for this program. However, restricted access to lab facilities made this impossible. We therefore pursued two alternative sources of FE materials.

First, we initiated a collaboration with researchers at the University of Texas at Austin, who provide us with epitaxial films of another ferroelectric material, BaTiO<sub>3</sub>. Although this material has a much lower surface polarization than PZT, we confirmed successful modulation of the WS<sub>2</sub> optical emission with the FE domains, thereby extending this capability to another FE material and demonstrating that control of the TMD properties is not unique to PZT. Second, a new commercial vendor coincidentally began developing a line of epitaxial PZT films, and we

have signed a non-disclosure agreement with Sumitomo Precision Products to provide us with their epitaxial wafers for this program in return for certain characterization. We have written FE domains into these films, transferred WS<sub>2</sub> monolayers onto them, and confirmed successful modulation of the WS<sub>2</sub> optical emission with the FE domains. We will continue to use these new PZT films for this program.

In an effort to determine the dominant factor producing the modulation of the TMD optical properties -- surface charge transfer or electric field from the FE polarization domains -- we initiated both theoretical and experimental work. Experimentally, we can distinguish these two contributions by inserting either a few layer film of hBN between the FE and TMD to block charge transfer, or a layer of graphene oxide to screen out any electric field. We fabricated samples with exfoliated hBN, but unfortunately either the quality of the hBN or the fabrication process resulted in new defect features appearing in the photoluminescence spectrum which compromised interpretation. Because hBN generally results in suppression of defect emission, we believe that we simply need to improve the sample fabrication process. Calculations were begun to determine changes in electrostatic potential at the surface of a poled ferroelectric and the role of H and OH ions adsorbed on the surface from the air ambient.

Monolayer WSe<sub>2</sub> is known to host defect states that are robust single photon emitters (SPEs), also known as quantum emitters. We have demonstrated that a gate voltage can both suppress emission of unwanted classical background light, and also select the wavelength of the active SPE -- both are extremely desirable for technological applications. Therefore, positive and negative polarization domains written into the FE onto which the monolayer WSe<sub>2</sub> is transferred should have similar effects. Preliminary data indicate that SPEs form preferentially on the up polarization domains, as evidenced by sharp discrete lines in the photoluminescence spectra. To confirm that these sharp lines are indeed SPEs, we need to measure the second order autocorrelation function,  $g_2(0)$ . We have previously relied upon our collaborators at the Air Force Research Lab to perform these measurements. However, covid has impacted lab occupancy at AFRL more severely than at NRL, and it has not been possible to acquire these essential data. Consequently, we have expended great effort to set up our own system to make these measurements at NRL, and expect this to be operational in Q1 of FY22.

We have begun efforts to demonstrate that the FE domains can control the properties of ultrathin ferromagnetic films using exfoliated flakes of Fe<sub>3</sub>GeTe<sub>2</sub> (FGT), a van der Waals ferromagnet with a bulk Curie temperature of 220K and an out-of-plane easy axis. The Curie temperature depends strongly upon the FGT thickness, and is strongly reduced for very thin films, e.g. it is 10K for a 3nm thick film. We have found that 8nm thick FGT flakes exfoliated onto BTO exhibit a Curie temperature of ~ 100K, with pronounced changes to the magnetic anisotropy. We are pursuing control experiments to determine whether this is due to the polarization domains, or to strain effects, or to a thickness dependence.

We attempted to synthesize the hyper-ferroelectric material In<sub>2</sub>Se<sub>3</sub> by molecular beam epitaxy. In<sub>2</sub>Se<sub>3</sub> exhibits several polytypes, and only the alpha phase is hyper-ferroelectric. Although we utilized a number of different substrates, buffer layers, growth temperatures and growth

procedures, we are only able to stabilize the beta phase, which is not ferroelectric. Effort will continue to realize the desired alpha phase.

## **FY20**

FY20 was a very challenging year for experimental work, as the covid operating posture severely restricted access to the extensive base of experimental equipment which forms the backbone of many NRL base programs. In spite of this, significant preliminary progress was made on several research goals.

- demonstrated that ferroelectric (FE) polarization domains in a lead zirconium titanate (PZT) film control the room temperature optical properties, specifically the photoluminescence (PL) intensity and spectral distribution, in a monolayer of MoSe<sub>2</sub> which was mechanically transferred onto the poled PZT film. This further confirms the fundamental hypothesis of our objectives and technical approach.
- obtained preliminary evidence that the FE domains in a PZT film can be used to localize single photon emitters (SPEs) in a WSe<sub>2</sub> monolayer transferred onto the PZT. Specifically, we observed very sharp PL emission peaks consistent with SPE from the portions of the WSe<sub>2</sub> monolayer which lie on a positive polarization domain rather than on the negative domain.
- demonstrated that FE materials other than PZT can be used to control and modulate the properties of single monolayer materials, and the degree of control appears to scale with the surface charge density of the FE material. Specifically, we observed modulation of the PL intensity of a WS<sub>2</sub> monolayer on a film of barium titanate, which has about one third the surface charge density of PZT.
- initial efforts were made to grow a new 2D ferroelectric material, In<sub>2</sub>Se<sub>3</sub>, by molecular beam epitaxy. This material is especially attractive for this program because as a van der Waals material, it should be very amenable to integration with other 2D materials such as WSe<sub>2</sub>. Although we were able to improve the film morphology, all growths resulted in Se-deficient samples which exhibited the beta phase rather than the desired FE alpha phase. This will be corrected in future growths.
- theoretical work was begun to determine changes in electrostatic potential at the surface of a poled ferroelectric due to adsorbate compensation. Such changes will impact the degree to which the FE can modulate the properties of the monolayer transition metal dichalcogenide laid on top due to partial screening of the polarization dipoles. Initial calculations were performed for water molecules on lead titanate surfaces, and indicated the formation of adsorbed OH<sup>-</sup> and H<sup>+</sup> ions due to dissociation of the H<sub>2</sub>O.
- we continued to improve the quality of 2D monolayer materials grown at NRL and understand their optical properties, as demonstrated by the following publications:

Refereed Publication: Prominent room temperature valley polarization in WS<sub>2</sub>/graphene heterostructures grown by chemical vapor deposition; I. Paradisanos , K. M. McCreary , D. Adinehloo, L. Mouchliadis, J. T. Robinson, Hsun-Jen Chuang, A. T.

Hanbicki, V. Perebeinos, B. T. Jonker, E. Stratakis, and G. Kioseoglou, *Appl. Phys. Lett.* 116, 203102 (May 2020); <https://doi.org/10.1063/5.0002396>. NRL/JA/6390/19/479; 19-1231-4214

Refereed Publication: Synthesis of High-Quality Monolayer MoS<sub>2</sub> by Direct Liquid Injection, Kathleen M. McCreary, Enrique D. Cobas, Aubrey T. Hanbicki, Matthew R. Rosenberger, Hsun-Jen Chuang, Saujan V. Sivaram, Vladimir P. Oleshko, and B.T. Jonker. *ACS Appl. Mater. Interfaces* 12, 9580-9588 (Jan 2020). NRL/JA/6390/19/480; 19-1231-4209

## Publications

1. Ferroelectric modulation of quantum emitters in monolayer WS<sub>2</sub>, Sung-Joon Lee, Hsun-Jen Chuang, Andrew Yeats, Kathleen M. McCreary, Dante J. O'Hara, Berend T. Jonker (NRL/6305/JA--2023/3). *Under review*.
2. Interlayer Exciton-Phonon Bound State in Bi<sub>2</sub>Se<sub>3</sub>/monolayer WS<sub>2</sub> van der Waals Heterostructures; Zachariah Hennighausen, Jisoo Moon, Kathleen M. McCreary, Connie H. Li, Olaf M. van't Erve and Berend T. Jonker. *ACS Nano* 17, 2529-2536 (January 2023). <https://doi.org/10.1021/acsnano.2c10313>; NRL/6390/JA--2022/15
3. Magneto-Optical Measurements of the Negatively Charged 2s Exciton in WSe<sub>2</sub>, J.C. Sell, J.R. Vannucci, D.G. Suarez-Forero, B. Cao, D.W. Session, H.-J. Chuang, K.M. McCreary, M.R. Rosenberger, B.T. Jonker, S. Mittal, M. Hafezi; *Phys. Rev. B* 106, L081409 (2022) NRL/6390/JA--2022/1
4. Laser-Patterned Submicrometer Bi<sub>2</sub>Se<sub>3</sub>-WS<sub>2</sub> Pixels with Tunable Circular Polarization at Room Temperature. Hennighausen, Z.; Wickramaratne, D.; McCreary, K. M.; Hudak, B. M.; Brintlinger, T.; Chuang, H.-J.; Noyan, M. A.; Jonker, B. T.; Stroud, R. M.; van 't Erve, O. M. *ACS Appl. Mater. Interfaces* 2022, 14 (7), 9504-9514. <https://doi.org/10.1021/acsnano.2c10313>. NRL/6390/JA--2022/15
5. Room-temperature oxygen transport in nano-thin Bi<sub>x</sub>O<sub>y</sub>Se<sub>z</sub> enables precision modulation of 2D materials, Zachariah Hennighausen, Bethany M. Hudak, Madeleine Phillips, Jisoo Moon, Kathleen M. McCreary, Hsun-Jen Chuang, Matthew R. Rosenberger, Berend T. Jonker, Connie H. Li, Rhonda M. Stroud, and Olaf M. van 't Erve. *ACS Nano* 16, 9, 13969-13981 (8 Sept 2022), <https://doi.org/10.1021/acsnano.2c03367>. NRL/6390/JA--2022/7
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### Patents

- Two dimensional materials integrated with multiferroic layers, B.T. Jonker, Navy case # 104,148 – US2 (method).
- Two dimensional materials integrated with multiferroic layers, B.T. Jonker, Navy case # 104,148 – US3 (structure). Patent issued 14 November 2023.
- Two dimensional materials integrated with multiferroic layers, B.T. Jonker, Navy case # 104,148 – US4. Patent filed 3 October 2023.
- Lateral Heterojunctions in 2D Materials by Integrating with Multiferroic Layers; Navy Case 104205-US2; Patent # 11,476,353 issued 18 October 2022.
- Light-emitting Devices having Lateral Heterojunctions in 2D Materials Integrated with Multiferroic Layers; Navy Case 104205-US3; Patent application filed 29 Sept 2022.
- Lateral Heterojunctions in 2D Materials by Integrating with Multiferroic Layers; Navy Case 104205-US4, patent issued 6 Feb 2024.
- Ferroelectric modulation of quantum emitters in monolayer WS<sub>2</sub>, Provisional patent 211878-US1 filed 30 Nov 2023.
- Navy Case 210973 - Invention Disclosure - Nano-thin BixO<sub>y</sub>Se<sub>z</sub> low-temperature oxygen transporter membrane for oxygen transport, separation, and two-dimensional (2D) material manipulation. Zachariah B. Hennighausen, Bethany M. Hudak, Madeleine Phillips, Olaf M.J. van 't Erve. 4 Feb 2022. NRL/6390/OT--2022/2
- Navy Case 210154-US2 - Patent Application for Laser-Written Submicron Pixels with Tunable Circular Polarization and Write-Read-Erase-Reuse Capability on a Nano Material or Two-Dimensional Heterostructure at Room Temperature. Zachariah Hennighausen, Kathleen McCreary, Olaf M J van't Erve, and Berend Jonker. 18 Mar 2022. NRL/6390/OT--2022/6
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### Transitions

- Hybrid 2D/3D Ferroic Heterostructures for Advanced Electronic Functionalities, funded by AFOSR. NRL JON 63-1P54

