SEEP-IT National Workshop on 2D Semiconducting Layered Materials Towards Quantum, Photonics, and Microelectronics to Fuel Innovations and Workforce Development



SEEP-IT
ENGINEERING THE FUTURE
with electronics, photonics and sensors

Workshop Final Report compiled by
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PI & Director, Department of Energy (DOE), National Nuclear Security Administration (NNSA), SEEP-IT Consortium

June 2026

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Preface

Semiconductors have profoundly impacted society with consistent technological advances over several decades, ultimately shaping communications, transportation, manufacturing, healthcare, and sensors for the internet-of-things (IoT). Starting with the early microprocessors in the 1970s comprised of a few thousand transistors, and fast forwarding to the current generation of microprocessors with more than 10 billion transistors per chip, the semiconductor industry is a testament to human ingenuity. While device miniaturization continues to scale down to smaller feature sizes, energy consumption from microprocessors has exploded in recent years.

This dramatic increase in energy consumption is driven by three key contributors: the use of Artificial Intelligence (AI) and Machine Learning (ML) algorithms to analyze large volumes of data, the fundamental energy inefficiency of the von Neumann architecture used in modern digital computing, and the growing use of microelectronics in broad sectors of society. Projections suggest that semiconductors are likely to consume nearly 25% of global energy production by 2030. Consequently, semiconductor-related energy use is a topic at the forefront of industry and government deliberations. Within the United States, semiconductors also underpin several national initiatives such as the National CHIPS for America Act, the National Photonics Initiative, and the National Quantum Initiative.

In this landscape, silicon and related bulk semiconductors are finding it increasingly challenging to meet modern computing demands. Moreover, with emerging *Moore-than-Moore* technologies, greater functionality in microelectronic systems is needed including flexible and wearable electronics, multi-modal sensors for surveillance, and quantum-enhanced systems for computation, sensing, and communication. Among emerging families of semiconductors are the two-dimensional (2D) layered materials, which hold promise for overcoming existing bottlenecks faced by conventional bulk three-dimensional (3D) semiconducting platforms. These 2D materials also offer possibilities for new and disruptive capabilities due to their strong interactions with applied electromagnetic fields.

Two-dimensional semiconductors, like conducting 2D graphene, can be isolated in their monolayer form and heterogeneously integrated through vertical stacking of van der Waals crystalline sheets. Libraries of crystals with specific electrical, thermal, optical, and mechanical properties have been realized in recent years. Among these hundreds of 2D materials, graphene, transition metal dichalcogenides (TMDCs), and hexagonal boron nitride (hBN) have received the most attention to date due to their high chemical stability and electronic properties spanning (semi)metals, semiconductors, and dielectrics.

The *SEEP-IT National Workshop on 2D Semiconducting Layered Materials Towards Quantum, Photonics, and Microelectronics to Fuel Innovations and Workforce Development* was an important and timely forum, featuring perspectives from leading researchers within academia, national laboratories, and industry. Topics discussed at the workshop ranged from basic science and quantum effects in 2D materials to more applied areas involving the integration of 2D semiconductors within microelectronics platforms.

The takeaways from the workshop fall into three distinct yet synergistic categories. The first category relates to the need for co-design between theory and experiment to build the fundamental understanding and knowledge of structure-property relationships between defects in 2D semiconductors and their quantum photonic emission properties. The integration of theory with AI and ML to predict the properties of new structural defects in 2D semiconductors, coupled with

fundamental innovations in tool design for *in-situ* imaging, will undoubtedly accelerate experimental efforts and future innovations.

The second category relates to the need for co-design between scalable 2D material synthesis and transfer methodologies to accelerate heterogeneous process integration with current semiconductor platforms. This goal requires the development of new tools and standardization processes through collaborative exchange mechanisms between academia, government laboratories, and industry in an effort to realize a lab-to-fab technology pathway for 2D materials. Key challenges for heterogeneous integration include strict thermal budgets, adherence to contamination control, and careful sequencing of process flows.

The third category relates to the urgent need for innovative approaches in educational practices given the national shortfall in skilled workers with expertise in semiconductor materials, semiconductor manufacturing, and quantum technologies. Given that traditional training methods alone are unable to meet the growing demand for the semiconductor workforce, innovations in pedagogy and engagement are needed throughout the educational pipeline.

Overall, this important workshop has confirmed that sustained government support will be vital in establishing the innovation ecosystem for 2D semiconductors in order to accelerate impactful deployment of 2D materials in quantum, photonic, and electronic technologies. The cross-cutting final recommendations discussed in this workshop final report will be valuable in guiding the development of future funding initiatives for research and workforce development efforts, and for expanded collaborative mechanisms at the intersection of academia, government laboratories, and industry.

Professor Mark C. Hersam

Walter. P. Murphy Professor of Materials Science and Engineering
Professor of Electrical and Computer Engineering and Chemistry (by courtesy)
Chair, Department of Materials Science and Engineering
Director, Materials Research Science and Engineering Center (MRSEC)
Northwestern University, Evanston, IL 60208-3108, USA
Member of the US National Academy of Engineering (NAE)
Fellow: AAA&S, AAAS, ACS, IEEE, MRS, APS, SPIE, AVS

1.0 Executive Summary

Over the past two decades, a rich library of van der Waals materials[1,2,3] has been documented which includes semiconducting transition metal dichalcogenides (e.g., MoS_2 and WSe_2), III-VI layered semiconductors (e.g., GaSe and InSe), mono-elemental semiconductors (e.g., phosphorene and silicene), dielectrics (e.g., h-BN), superconductors (e.g., $NbSe_2$), and conductors (e.g., graphene). The demonstration to synthetically nucleate or mechanically exfoliate individual crystallites from the bulk has widened the scope to design intriguing prototypical devices given the emergent electronic, optical, thermal and strain-dependent properties two-dimensional layered materials (2DLMs) possess. Such properties have led 2DLMs to be considered as viable candidates for "*Electronics Beyond Moore's Law*," where the microelectronics field has witnessed a monumental technological and societal impact driven by the invention of the Silicon transistor.[4,5] The inherent band gap in some of the transition metal dichalcogenides (TMDCs), coupled with the potential for atomically-smooth, pristine interfaces, can enable low-power and low-dissipation devices for ultra-scaled, thin-body transistors including their heterogeneous integration with Si chips.[6] The strong light-matter interactions[7,8] seen in many of the 2DLMs are also reasons for their consideration in quantum photonics applications. This includes light emission features in 2DLMs which are modulated via defect-engineering for the realization of quantum emitters needed in the burgeoning field of quantum information sciences (QIS).[9,10]

The light-matter interactions in 2DLMs and their heterogeneous integration through vertical stacking are topics currently being explored within the Department of Energy (DOE) National Nuclear Security Administration (NNSA) SEEP-IT Consortium [**S**ensors, **E**nergy-efficient **E**lectronics, **P**hotonics with Two-dimensional Materials and **I**ntegrated **T**echnologies, led by the University of North Texas (UNT)]. Besides UNT, SEEP-IT involves a team of researchers from the University of Texas at Arlington (UTA), University of Arkansas, Pine Bluff (UA-PB), Argonne National Laboratory (Argonne) and Sandia National Laboratory (Sandia).

Hosted as part of the SEEP-IT Consortium, this *SEEP-IT National Workshop on 2D Semiconducting Layered Materials Towards Quantum, Photonics, and Microelectronics to Fuel Innovations and Workforce Development*, provided a motivation to expand the research and educational discussions beyond the immediate consortium participants. This was done by involving the broader technical community, including from Argonne, to explore synergies and alignment with potential future initiatives. The invited speakers at the workshop are leaders in the physics, chemistry and engineering of 2DLMs, quantum systems, microelectronics, and photonics. The discussions spanned fundamental science, devices and applications, as well as educational practices in these areas for STEM workforce development. Strategies to amplify the domestic workforce pipeline in these strategic areas is particularly timely given that quantum technologies and emergent semiconductors, including those based on 2DLMs, are well-aligned with the goals of the "Creating Helpful Incentives to Produce Semiconductors (CHIPS) for America Act,"[11] the National Photonics Initiative,[12] and the National Quantum Initiative.[13] Such initiatives are all critical for national security, technology leadership and the economic interests of the United States.

The Principal Investigator (PI) and Director of the DOE/NNSA SEEP-IT Consortium, Dr. Anupama Kaul, PACCAR Professor of Engineering at UNT's College of Engineering, served as the workshop chair. She worked with her organizing team at UNT and Argonne, including SEEP-IT Argonne collaborator and workshop co-chair, Dr. Anirudha Sumant, to launch this two-day Workshop event held at the Advanced Photon Source, Argonne, on December 10th-11th, 2024. A total of about 50 invited participants, including world-leading experts, engaged in a fruitful

discourse, where Figure 1 provides a mapping of the workshop participants in terms of (a) geography and (b) sector.

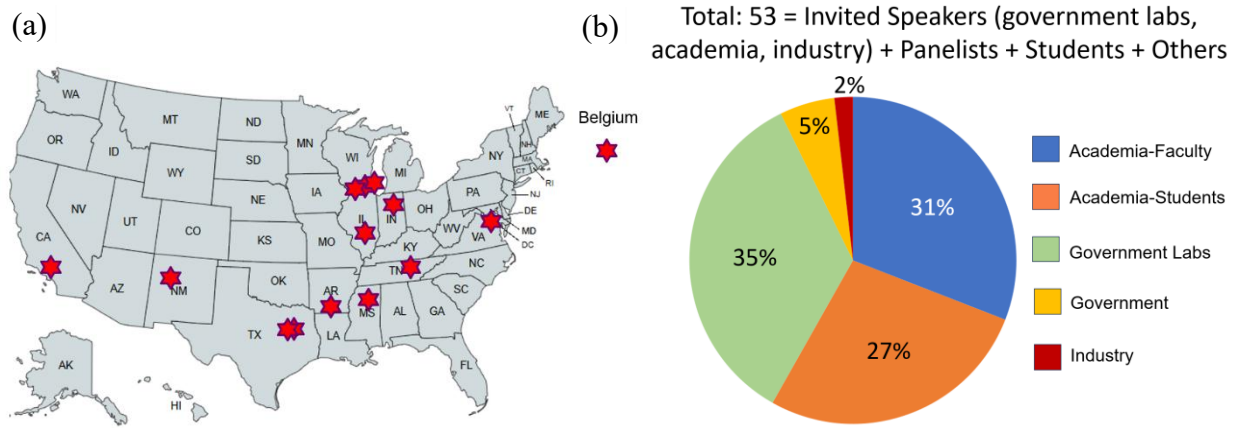


Figure 1. (a) Geographical distribution of participants at the workshop. (b) Breakdown of participants at workshop from the various sectors: academia, government labs, government and industry.

The three primary goals of the workshop are listed below, and these three goals were closely aligned with the three Working Groups (WGs) formed, elaborated upon further in the Overview Section (Section 2.0).

Goal 1: *showcase recent scientific advances in photonic and quantum properties of 2DLMs, as well as their synthesis, scalability and heterogeneous integration;*

Goal 2: *highlight mechanisms to strengthen connections between academia, national labs and industry to develop an innovation ecosystem to advance the translational use of 2DLMs in quantum and advanced microelectronics platforms;*

Goal 3: *discuss innovative educational strategies for recruiting and retaining domestic students to create a vibrant workforce pipeline having the necessary skills towards quantum and semiconductor technologies.*

Workshop Organizing Committee and Working Group (WG) Leads/Scribes

Prior international workshops Prof. Anupama Kaul has organized and led over the past decade[14,15,16] have subsequently resulted in the creation of new funding opportunities.[17,18] The current workshop under the DOE/NNSA/MSIPP SEEP-IT Consortium, involved the following members of the organizing committee from UNT and Argonne, while the Working Group (WG) Leads and Scribes were from various national laboratories, academia and industry, as shown below.

Organizing Committee

Workshop Chair

Prof. Anupama B. Kaul

PACCAR Professor of Engineering
Department of Materials Science & Engineering
Department of Electrical Engineering (joint)
Director, Nanoscale Materials & Devices Lab (NMDL)
Director and PI, DOE-NNSA SEEP-IT Consortium
University of North Texas, Denton

Co-Chair

Dr. Anirudha V. Sumant

Group Leader, Nanofabrication and Devices and Materials Scientist, Nanoscience
Center for Nanoscale Materials (CNM)
Argonne National Laboratory

Workshop Logistics Coordinators

Ms. Allyson Tesky

UNT Workshop Logistics Coordinator
University of North Texas, Denton

Ms. Lynnean Celmer

Argonne Workshop Logistics Coordinator
Argonne National Laboratory

Mr. Min Hong

Argonne Workshop Logistics Coordinator
Argonne National Laboratory

Working Group 1: ***Discovery-driven research on quantum properties, light-matter interactions, strain, synthesis, scalability***

Dr. An-Ping Li
Lead
Distinguished Staff Scientist, Group Leader, Theme Leader, Heterogeneities in Quantum Materials, Oak Ridge National Lab (ORNL)

Prof. Matthew Grayson
Lead
Professor, Electrical and Computer Engineering, Northwestern University

Dr. Andreas Gottscholl
Scribe
Jet Propulsion Laboratory, Caltech, NASA, Pasadena, CA USA; Applied Materials, Sunnyvale, CA

Dr. Akshay Wali
Scribe
Argonne National Laboratory, Lemont, IL

Working Group 2: ***Innovation ecosystems centered around 2D materials for translational research and alignment with government labs/industry needs towards Quantum/CHIPS***

Prof. Arend van der Zande
Lead
Associate Professor, Department of Materials Science and Engineering and Mechanical Science and Engineering; U. Illinois, Urbana-Champaign (UIUC)

Dr. Ihab El-Kady
Lead
Distinguished Member of Technical Staff, National Photonics Center, Sandia National Laboratory

Dr. Cesar Javier Lockhart de la Rosa
Scribe
IMEC, Belgium

Dr. Sujan Aryal
Scribe
University of North Texas

Working Group 3: ***Innovations in educational strategies to recruit and prepare a vibrant domestic quantum/CHIPS workforce pipeline***

Prof. Peter Bermel
Lead
Elmore Professor of Electrical and Computer Engineering, Associate Director of Graduate Admissions, Purdue University

Prof. Ann Cavallo
Lead
Assistant Vice Provost/ Director, Center for Research on Teaching and Learning Excellence, Distinguished University Professor of Science Education, University of Texas, Arlington

Dr. Steve Kamau
Scribe
University of North Texas

The three Working Group (WG) Leads (L) and Scribes (S), [**WG#1**-(L): Drs. An-Ping Li and Matthew Grayson, and (S): Drs. Andreas Gottscholl and Akshay Wali; **WG#2**-(L): Drs. Arend van der Zande and Ihab El-Kady, and (S): Drs. Cesar Javier Lockhart de la Rosa and Sujan Aryal; **WG#3-**(L): Drs. Peter Bermel and Ann Cavallo, and (S): Dr. Steven Kamau] provided WG

Summary Reports through the discussions held during and after this event. These WG Summary Reports are included in Section 5.0 and formed the basis for the compilation of the Final Recommendations (*R*) from this workshop, namely *R1 – R7*, delineated in Section 6.0. Here, in Section 2.0, a deeper elaboration on the scientific and technical context is presented, further solidifying the motivation for this workshop, while Sections 3.0 and 4.0 illustrate the specific topics covered, agenda and participants list. Overall, the workshop proved to be a very valuable forum, drawing enthusiastic participation from the attendees to discuss important topics at the intersection of various domains. The cross-cutting final recommendations from this workshop serve as a guide for future funding initiatives central to 2D semiconductors and workforce development efforts, as they align with important national needs.

2.0 Overview

The new scientific and technological opportunities offered by the rapidly expanding family of 2D semiconducting layered materials have already attracted significant investments worldwide, including through the European Commission's (EU's) Graphene Flagship Program,[19] the US National Science Foundation (NSF),[20,21,22] and basic science institutes in Korea,[23] as just some key examples. Properties of 2DLMs that have captured the attention of the research community includes their high carrier mobility,[24,25] topological electronic phases,[26] strong light-matter interactions,[27] exciton-based multibody dynamics,[28] non-linear optical features,[29] and strain-modulated emission.[30,31,32] These attributes have collectively advanced the use of 2DLMs in devices such as photodetectors,[33] strain sensors,[34] *p-n* junctions,[35] solar cells,[36] and low-threshold lasers.[37,38] Besides the individual crystallites, their pristine interfacial structural attributes also facilitate the lego-like construction of van der Waals (vdW) heterostructures,[39] in a single system-on-chip framework, from the bottom-up.

Within quantum photonics, the area of QIS is growing rapidly,[40,41] where the use of photons for information processing appears to be one avenue to address challenges for computational power beyond the Moore's Law realm. A central element for QIS applications[42,43] are single photon emitters (SPEs), where an ideal on-demand SPE emits exactly one photon at a time.[44,45,46] Recently, 2DLMs have shown practical appeal for QIS[47] which is directly driven by their unique layered crystalline structure.[48] This structural attribute of 2DLMs facilitates their integration with optical elements more easily than the SPEs in conventional three-dimensional (3D) solid-state materials, such as diamond and SiC. The emitters in 3D solid-state materials are typically buried deep within the bulk. While a diverse variety of material systems have been studied as viable SPE sources, including trapped ions, atoms, molecules, quantum dots and bulk solid-state emitters, the field is experiencing an upsurge given recent large-scale initiatives.[12,13]

Work on quantum emitters towards SPEs in 2DLMs began with WSe_2 through the native defects that reside in this material. While native defects maybe present in semiconducting materials owing to the unintentional incorporation of impurities during crystal synthesis, they can also be created intentionally through deterministic means. In 2DLMs, defects may range from vacancies or other point defects, but linear defects such as folds and dislocations are also commonly observed. The defects influence dynamics of excitons to localize them near defect sites, yielding localized emission. One of the best understood SPEs associated with defects in solid-state materials is the nitrogen-vacancy *(NV)* center in diamond[49] in its negatively charged form, N_V^{-1}. Studies on the N_V^{-1} energy level structure, excitation, and decay pathways have been carried out for more than a

decade, that have led to insights on the underlying mechanisms. In wide band gap 2DLMs such as h-BN, the deep energy levels are generated from point defects, namely boron-vacancies (V_B) and nitrogen-vacancies (V_N). Defects may also form if other atoms are substituted in for *B* or *N* atoms.[50] As noted, the SPEs from localized emitters in 2DLMs[51,52] were borne from pioneering research conducted first on semiconducting WSe_2,[53,54,55] which subsequently moved to h-BN.[56,57,58] These investigations have continued to progress,[59] and recently also include interlayer excitons and excitons localized in moiré superlattice potentials.[60,61]

Ideally, the SPEs should be created deterministically for scalable avenues to emerge for viable QIS applications in the future. This requires an understanding of the detailed structure of the precise atomic location, spatial separation, and environment of the responsible defects correlated to the ensuing optical emission properties. Scanning tunneling microscopy (STM)[62] is one of the few techniques that is capable of addressing this challenge, as it is equipped with advanced imaging, spectroscopy, and manipulation capabilities, all at the individual atomic level. These capabilities make it possible to identify individual defects and even control or create the desired defect structures. Clearly, this area of research involving 2DLMs and defect engineering for quantum is in the midst of tackling fundamental scientific questions, evident through the recent exponential growth in research publications.

At the same time, the breadth of chemically synthesized compositions of 2DLMs is well established. Often, a primary goal for synthesis efforts is to yield 2D monolayer membranes over large areas, as well as their heterogeneous integration vertically.[63] Large-area scaling has progressed successfully over the past seven decades within the semiconductor microelectronics industry based on conventional 3D bulk semiconductors such as Si according to Moore's Law.[64] However, as feature sizes continue to shrink in the few nanometers range, including in dense gate-all-around (GAA) field-effect-transistor (FET) architectures,[65] the performance concerns involving speed, power consumption, and heat dissipation of nanoscale transistors affords an opportunity for 2DLMs, given their unique structural attributes and properties, to address some of the pressing technical bottlenecks for classical computing and microelectronics more broadly.

In order for 2DLMs to have a meaningful impact on the microelectronics industry, their scalability and synthesis over large areas is a key prerequisite. Scalability and the translational use of 2DLMs into industry-relevant platforms shares common historical challenges encountered by any new and emergent material system,[66] often taking decades to reach fruition. In this regard, emulating successes from initiatives worldwide, such as through the Graphene Flagship is timely, given that some 2DLMs are now incorporated into commercial composites, while more than 100 products have been launched to market, facilitated by the Flagship. These exceptional outcomes were achieved through a carefully orchestrated innovation ecosystem spearheaded in Europe over the course of a decade, composed of academics and industry working towards common goals. Through this alignment, some of the key challenges were addressed by establishing standards and the standardization of manufacturing processes, as discussed in the Graphene Flagship's 10 year assessment report;[67] further research and development innovations continue currently under the new Horizon Europe partnership, specifically through the *Innovative Advanced Materials for Europe* (IAM4EU). These perspectives are valuable and synergistic to research and integration[68]of 2DLMs towards microelectronics and quantum platforms in the US.

On the practical side with regard to the development of human capital in this domain, the US STEM community comprised of academics, administrators and working professionals, is well-aware of the significant shortage of domestic talent available to fill imminent needs for the microelectronics and semiconductor industry.[11] Similar workforce challenges are expected to arise

in the burgeoning QIS domain for future industry, as well as attracting talent for such positions in the federal government.[69] New graduates across the education pipeline in the US having the necessary skills and knowledge in these topical areas will undoubtedly help accelerate technological innovation for long-term advancement. As an example, this awareness nationally has led to the creation of new curriculum for early bachelors and associates degrees, infrastructure upgrades, and research supporting semiconductor fabrication innovation which should bolster domestic semiconductor capacity and growth through a key focus on education.[70] Emulation of such coordinated educational initiatives spreading across geographies in the US will be important, so meaningful impacts on workforce development nationally are accelerated, showing benefits in the near-term.

At this workshop, leading experts from within and external to the SEEP-IT Consortium were invited to discuss advances made in fundamental research on the photonic and quantum effects prevalent in 2DLMs towards quantum and microelectronics, translational adoption of these materials in the semiconductor industry, as well as STEM education for workforce development. These discussions were held through invited talks, panel discussions, poster sessions and working group discussions, as detailed in the workshop agenda (Section 4.0). The 50 or so workshop participants distributed themselves into three working groups shown below on Day 1, where the Leads and Scribes captured the main discussion points which they then presented on Day 2.

Working Group 1: "Discovery-driven research on quantum properties, light-matter interactions, strain, synthesis and scalability"

Working Group 2: "Innovation ecosystems centered around 2D materials for translational research and alignment with government labs/industry needs towards Quantum/CHIPS"

Working Group 3: "Innovations in educational strategies to recruit and prepare a vibrant domestic quantum/CHIPS workforce pipeline"

As noted, the workshop was borne through activities within the SEEP-IT Consortium directed by Prof. Kaul at UNT, and her discretionary funding sources supported associated costs for hosting this meeting, with the aim to further bolster future research alignments through collaborative discussions. Prior to the workshop, Prof. Kaul organized several teleconferences with the Working Group Leads and Scribes to discuss the break-out questions unique to each working group. The organizing committee members from UNT and Argonne also coordinated periodic discussions in the months preceding the workshop to discuss logistics. The organizing team at UNT developed a workshop website for participants to register for this meeting, allowing the Argonne organizing committee team members to then issue on-site visitor access passes. The Argonne organizing committee team members also provided mechanisms to facilitate on-site tours of the exceptional facilities at Argonne.

3.0 List of Topics

The invited talks, panel discussions, poster presentations and working group discussions helped the participants gain insights into the latest developments related to Goals 1, 2 and 3, noted in Section 1.0. Provided below are the topics that were covered at the workshop on Day 1 and Day 2 within Sessions 1 – 8.

Session 1: "Quantum/Photonic/Strain/Thermal Properties in 2D Layered Materials"

Session 2: "Synthesis, Scalability and Characterization Techniques for 2D Layered Materials"

Session 3: "Innovation Ecosystems Related to Quantum/Microelectronics to Align with Industry and Government Labs Needs"

Session 4: "Educational Strategies for Workforce Development Towards Quantum/Microelectronics"

Session 5: "Panel Discussion on Broadening Participation Towards Quantum/CHIPS"

Session 6: "Poster Session for Early Career Researchers"

Session 7: "Student-centric initiatives to promote engagement with DOE/NNSA Labs: Perspectives from SEEP-IT Consortium Students and their DOE/NNSA Labs Mentors"

Session 8: "Break-out summary presentations to address opportunities and challenges"

Prior to Session 1, the "*Opening Session and Keynotes*" brought important perspectives from leaders in government, academia, and national labs. Specifically, these included Dr. Kawtar Hafidi, Director of Physics and Science Directorate (Argonne) and Ms. Betsy Snell, Program Manager, DOE-NNSA-MSIPP Program Office, who provided Opening Remarks. The Keynote talks were provided by: Prof. Giulia Galli, Liew Family Professor of Molecular Engineering, Pritzker School of Molecular Engineering, University of Chicago; and Dr. Amanda Petford-Long, Division Director, Materials Science, Argonne Distinguished Fellow; Director, Argonne Microelectronics Institute, Argonne; Professor, Materials Science and Engineering, Northwestern University.

4.0 Workshop Agenda and Participants

4.1 Workshop Program

SEEP-IT National Workshop on 2D Semiconducting Layered Materials Towards Quantum, Photonics and Microelectronics to Fuel Innovations and Workforce Development

Meeting Location: Argonne National Laboratory (Argonne), Lemont, Illinois

Building: Advanced Photon Source (APS) Conference Center, Bldg. 402

Day 1 - December 10th (Tuesday), 2024			
Workshop Registration - Day 1 - Building 402 Lower Gallery (E0100) - Registration Desk			
Registration begins @ 7:30 am			
All Sessions and Invited Talks will take place in Bldg. 402, Lower Gallery E0100 Conference Center			
Workshop Opening Session and Keynotes			
Time	**Speaker**	**Affiliation**	**Talk Title**
8:15 am- 8:20 am	**Lynnean Celmer**	Argonne Campus - Meeting Logistics and Other Argonne-related Facilities	*Workshop Logistics Coordination*
8:20 am- 8:25 am	**Anupama Kaul (UNT),** Workshop Chair **Anirudha Sumant (Argonne),** Workshop Co-Chair	University of North Texas (UNT) Argonne National Laboratory DOE-NNSA-MSIPP SEEP-IT Consortium	*Welcome and Opening Remarks*
Dr. Anirudha Sumant, Workshop Co-Chair, to introduce Dr. Hafidi, Ms. Betsy Snell, Dr. Petford-Long, Dr. Galli			
8:25 am- 8:30 am	**Kawtar Hafidi**	Director of Physics and Science Directorate, Argonne National Laboratory	*Opening Remarks from Argonne Leadership*
8:30 am- 8:35 am	**Betsy Snell**	Program Manager, DOE-NNSA-MSIPP Program Office	*Opening Remarks from DOE-NNSA- MSIPP Leadership*
8:35 am-9:05 am	**Amanda Petford-Long**	Division Director, Materials Science, Argonne Distinguished Fellow; Director, Argonne Microelectronics Institute, Argonne; Professor, Materials Science and Engineering, Northwestern U.	*Keynote: Argonne's Microelectronics Initiative*
9:05 am-9:35 am	**Giulia Galli**	Liew Family Professor of Molecular Engineering, Pritzker School of Molecular Engineering, University of Chicago	*Keynote: Quantum Simulations for Quantum Technologies*
9:35 am-10:05 am	**Anupama Kaul,** Workshop Chair	PACCAR Professor of Engineering, Director DOE/NNSA/MSIPP SEEP-IT Consortium, University of North Texas (UNT)	*Workshop Overview, Goals & Outcomes*

10:05 am-10:10 am	**Allyson Tesky**	Workshop Student Lead Ambassador, SEEP- IT Consortium Graduate Student, UNT	*Workshop Logistics Coordination*
Morning Break			
Session 1: Quantum/Photonic/Strain/Thermal Properties in 2D Layered Materials ***Session Chair: An-Ping Li, Oak Ridge National Laboratory (ORNL); Scribe: Akshay Wali, Argonne National Laboratory***			
10:25 am-10:45 am	**Jeff Guest**	Group Leader, Experimental Physicist, Center for Nanoscale Materials (CNM), Argonne National Laboratory	*Understanding and Controlling Defects in 2D Materials on Atomic Length Scales for Quantum Information Science*
10:45 am-11:05 am	**Andreas Gottscholl**	Jet Propulsion Laboratory, National Aeronautics and Space Administration (NASA), Caltech	*Optical Accessible Spin Defects in Hexagonal Boron Nitride: Identification, Control and Application of the Negatively Charged Boron Vacancy*
11:05 am-11:25 am	**Arend van der Zande**	Associate Professor, Department of Materials Science and Engineering and Mechanical Science and Engineering; U. Illinois, Urbana-Champaign (UIUC)	*Straintronics in 2D Materials*
11:25 am-11:45 am	**Matthew Grayson**	Professor, Electrical and Computer Engineering, Northwestern University	*Novel 2D Transport Characterizations: All-Electrical Determination of Anisotropic Crystal Orientation and Conductivity Scaling for Tunable Impurity Densities*
11:45 am-12:05 pm	**Xu Han**	Assistant Scientist, Center for Nanoscale Materials (CNM), Argonne National Laboratory	*Development of Next-Generation Quantum Devices and Systems at Argonne CNM*
Working Lunch			
12:25 pm-12:45 pm	**Martin Holt**	Q-NEXT Lead on Extreme Scale Characterization; Group Leader - Electron and X-ray Microscopy/Scientist, Nanoscience	*Lunch Invited Speaker: Q-NEXT National Quantum Information Science Research Center*

Session 2: Synthesis, Scalability and Characterization Techniques for 2D Layered Materials ***Session Chair: Matthew Grayson, Northwestern U.; Scribe: Andreas Gottscholl, JPL-NASA-Caltech***			
1:00 pm-1:20 pm	**Mark Hersam**	Chair of Materials Science and Engineering (MSE), Walter P. Murphy Professor of MSE, Electrical and Computer Engineering; Chemistry, Director MRSEC, Northwestern University	*Two-Dimensional Neuromorphic Electronic Materials and Applications*
1:20 pm-1:40 pm	**Anirudha Sumant**	Group Leader, Center for Nanoscale Materials (CNM), Argonne National Laboratory; DOE Labs Partner of SEEP-IT Consortium	*Opportunities in Developing Efficient Electronics via Heterogeneous Integration of 2D and Semiconducting Materials with Diamond*
1:40 pm-2:00 pm	**An-Ping Li**	Distinguished Staff Scientist, Group Leader, Theme Leader, Heterogeneities in Quantum Materials, Oak Ridge National Lab (ORNL)	*Atomistic-level Understanding and Control of Defect States in 2D Layered Materials*
2:00 pm-2:20 pm	**Anupama Kaul**	PACCAR Professor of Engineering, Materials Science and Engineering; Electrical Engineering, UNT; Yuankun Lin, Professor of Physics, UNT; SEEP-IT Consortium Partners	*Optically-active van der Waals Solids Through Bottom-up and Top-down Synthesis Routes for Sensors and Quantum-enabled Devices*
2:20 pm-2:40 pm	**Roberto dos Reis**	Scientific Officer, Materials Science and Engineering & Vinayak Dravid, Northwestern University	*From Pixels to Properties: Integrating multimodal STEM and Machine Learning for Advanced Characterization of 2D Materials*
Workshop Group Photo			
Afternoon Break			
Session 3: Innovation Ecosystems Related to Quantum/Microelectronics to Align with Industry and Government Labs Needs ***Session Chair: Arend van der Zande, UIUC; Scribe: Sujan Aryal, UNT***			
3:10 pm-3:30 pm	**Cesar Javier Lockhart de la Rosa**	Program Manager, Exploratory Logic, IMEC, Belgium	*A Logic Roadmap for the FAB Compatible Integration of Low Dimensional Materials: Strategy, Challenges and Opportunities*
3:30 pm-3:50 pm	**Phillip Smith**	Strategic Programs Manager, Argonne National Laboratory	*Working with Argonne, a Partner in Innovation*

3:50 pm-4:10 pm	**Ihab El-Kady**	Distinguished Member of Technical Staff, National Photonics Center, Sandia National Laboratory	*A Group Theory-Based Approach to the Design and Amplification of Synthetic Nonlinearities*
Session 4: Educational Strategies for Workforce Development Towards Quantum/Microelectronics ***Session Chairs: Alice Sun, UT Arlington; Qinglong Jiang (UA-PB); Scribe: Ann Cavallo, UT Arlington***			
4:10 pm-4:30 pm	**Peter Bermel**	Elmore Professor of Electrical and Computer Engineering, Associate Director of Graduate Admissions; Purdue University	*Scalable Models for Microelectronics Workforce Development*
4:30 pm-4:50 pm	**Quinn Spadola**	Deputy Director, National Nanotechnology Coordination Office (STEM Education)	*Nanotechnology-Enabled: The Quantum and Micro/Nanoelectronics Workforce*
Session 5: Panel Discussion on Broadening Participation Towards Quantum/CHIPS ***Session Chairs: Peter Bermel, Purdue U.; Scribe: Steve Kamau, UNT***			
4:50 pm-5:40 pm	**Panelist A**	**Ann Cavallo**, Assistant Vice Provost & Director, Center for Research on Teaching & Learning Excellence, Distinguished University Professor of Science Education, UT Arlington (HSI); SEEP-IT Consortium Partner	
	Panelist B	**Qinglong Jiang**, Associate Professor of Chemistry and Physics, University of Arkansas, Pine Bluff (HBCU); SEEP-IT Consortium Partner	
	Panelist C	**Jermiah Billa,** Associate Professor and Chairperson, Department of Advanced Technologies, Alcorn State University, Mississippi; DOE-NNSA-MSIPP Consortium member	
	Panelist D	**Patrick Chu,** Manager, National Photonics Center, Sandia National Laboratory; SEEP-IT Consortium Partner	
	Panelist E	**Quinn Spadola,** Deputy Director, National Nanotechnology Coordination Office (NNCO)-STEM Education	
	Panelist F	**Robert Schuch,** University Partnership Program Manager, Argonne National Laboratory	

Session 6: Poster Session for Early Career Researchers [students, postdocs] upstairs in 402, Rm. E1100 / E1200 [posters mounted on easels with 4 ft x 4 ft foam boards] ***Poster Session Chair: Allyson Tesky, UNT*** ***Best Poster Award Judges: Yaowu Hao and Rasool Kenarangui, UT Arlington***			
5:40 pm-6:25 pm	**DOE-SEEP-IT Consortium Students & Staff; Argonne Postdoctoral Scholars & Staff**		
Working Dinner Discussions (Leads/Scribes Discuss Summaries with their WGs in Preparation for Day 2 Presentations)			
6:30 pm-7:45 pm	**Working Group 1** (Discovery-driven research on quantum properties, light-matter interactions, strain, synthesis, and scalability)	**Working Group 2** (Innovation ecosystems centered around 2D materials for translational research and alignment with government labs/industry needs towards Quantum/CHIPS)	**Working Group 3** (Innovations in educational strategies to recruit and prepare a vibrant domestic quantum/CHIPS workforce pipeline)
	Leads: An-Ping Li, ORNL; **Matthew Grayson**, NWU; **Scribes**: **Andreas Gottscholl,** JPL-NASA, **Akshay Wali**, Argonne; rest of participants	**Leads: Arend van der Zande,** UIUC, **Ihab El- Kady,** Sandia; **Scribes: Cesar Javier Lockhart de la Rosa,** IMEC, **Sujan Aryal,** UNT; rest of participants	**Leads: Peter Bermel,** Purdue U.**; Ann Cavallo,** UT Arlington; **Scribe: Steve Kamau**, UNT; rest of participants
Breakout Questions (BQ) for all speakers in Sessions 1-5, to address in last few mins of their talks (and to be summarized for presentations on Day 2 by Working Group Leads/Scribes)			
BQ1 - Are there significant opportunities and low-hanging fruits to be pursued in this topic?			
BQ2 - What are the major bottlenecks and challenges preventing us from reaping the maximal benefits from BQ1?			
BQ3 - Are there scientific, programmatic or institutional initiatives which will help overcome the challenges from BQ2 to facilitate progress?			

Day 2 - December 11th (Wednesday), 2024

All Sessions and Invited Talks will take place in Bldg. 402, Lower Gallery E0100 Conference Center

Session 7: Student-centric Initiatives to Promote Engagement with DOE/NNSA Labs; Perspectives from SEEP-IT Consortium Students and their DOE/NNSA Labs Mentors

Time	Speaker	Affiliation	Talk Title
Dr. Anupama Kaul, Workshop Chair, to introduce Ms. Betsy Snell			
8:30 am-8:50 am	**Betsy Snell**	DOE-NNSA-MSIPP Program Office	*Keynote Address: DOE-NNSA-MSIPP Program Office Leadership Perspectives*
8:50 am-9:10 am	**Robert Schuch**	University Partnership Program Manager, Argonne National Laboratory	*Overview of Argonne University Programs and Partnerships*

9:10 am-9:25 am	**Anirudha Sumant-** Argonne; **Chandler Lewis-** UNT SEEP-IT Student Intern	Argonne DOE Laboratory Mentor with SEEP-IT Student Intern (UNT)	Mentor/Student Perspectives Talk
9:25 am-9:40 am	**Patrick Chu/Ihab El-Kady-** Sandia National Laboratory; **Steve Kamau-** UNT SEEP-IT PhD Student	SNL-DOE-NNSA Laboratory Mentor with SEEP-IT Student Intern (UNT)	Mentor/Student Perspectives Talk
Morning Break			
Session 8: Break-out Summary Presentations to Address Opportunities and Challenges			
Time	**Working Groups**	**Working Group Topic**	**Summary Report from Leads/Scribes**
9:55 am-10:15 am [10 min report, 10 min discussion]	**Leads/Scribes - Working Group 1**	Discovery-driven research on quantum properties, light-matter interactions, strain, synthesis, scalability, etc.	**Draft Summary Report #1;** Leads: **An-Ping Li**, ORNL; **Matthew Grayson**, NWU; **Scribes**: **Andreas Gottscholl**, JPL-NASA, **Akshay Wali**, Argonne
10:15 am- 10:35 am [10 min report, 10 min discussion]	**Leads/Scribes - Working Group 2**	Innovation ecosystems centered around 2D materials for translational research and alignment with government labs/industry needs towards Quantum/CHIPS	**Draft Summary Report #2; Leads**: **Arend van der Zande**, UIUC, **Ihab El-Kady,** Sandia**; Scribes: Cesar Javier Lockhart de la Rosa,** IMEC**, Sujan Aryal,** UNT
10:35 am-10:55 am [10 min report, 10 min discussion]	**Leads/Scribes - Working Group 3**	Innovations in educational strategies to recruit and prepare a vibrant domestic quantum/CHIPS workforce pipeline	**Draft Summary Report #3; Leads: Peter Bermel,** Purdue U.**; Ann Cavallo,** UT Arlington; **Scribe: Steve Kamau,** UNT
10:55 am-11:05 am	**Workshop Best Poster Awards**	Poster Presenter Recognitions for Undergraduate & Graduate Students; Postdoctoral Scholars/Staff	Awards Presented by **Allyson Tesky**, UNT; **Yaowu Hao**, UT Arlington; **Rasool Kenarangui**, UT Arlington
11:05 am-11:15 am	**Closing Remarks**	Closing Remarks and Final Workshop Report Completion Schedule	Workshop Chair, **Anupama Kaul**-UNT Workshop Co-Chair, **Anirudha Sumant**- Argonne
Working Lunch			
11:35 am-11:45 am	**Constance A. Vanni**	Manager, Advanced Photon Source (APS) User Program	Overview of the Argonne APS User Program
11:45 am-11:55 am	**Katie Tietz**	User Program Coordinator, Center for Nanoscale Materials (CNM)	Overview of the Argonne CNM User Program
Argonne Laboratory Tours Commence at 12:15 pm for Workshop Participants			
12:30 pm-2:30 pm	**Argonne APS Tour**	Advanced Photon Source (APS) at Argonne	Argonne personnel from APS to guide tour

1:00 pm-2:00 pm	**Argonne CNM Tour**	Center for Nanoscale Materials (CNM) at Argonne	Argonne personnel from CNM to guide tour
12:30 pm-2:30 pm	**Argonne Museum Tour**	Nuclear Energy Exhibit Hall Museum	Argonne personnel from Museum to guide tour
Workshop Adjourned (once tours finish between 2:30-3:00 pm)			

4.2 List of Participants

First Name	Last Name	Organization	E-Mail
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4.3 Picture Gallery



Figure 2. Group photo of the workshop participants, Dec. 10, 2024.



Figure 3. Interactions captured of workshop participants and invited speakers.



Figure 4. Some of the leading speakers at the SEEP-IT National Workshop. **Top Panel (left-to-right)**: Ms. Betsy Snell (Program Manager, DOE/NNSA/MSIPP Program Office), Prof. Mark Hersam (Northwestern University); **Middle Panel**: Dr. Martin Holt (Argonne National Laboratory), Dr. An-Ping Li (Oak-ridge National Laboratory); **Bottom Panel**: Dr. Andreas Gottscholl (Jet Propulsion Laboratory, Caltech, NASA, now Applied Materials), Prof. Matthew Grayson (Northwestern University).



Figure 5. Some of the leading speakers at the SEEP-IT National Workshop. **Top Panel (left-to-right)**: Prof. Arend van der Zande (University of Illinois, Urbana-Champaign), workshop participants; **Middle Panel:** Phillip Smith (Argonne National Laboratory), Dr. Cesar Javier Lockhart de la Rosa (IMEC); **Bottom Panel:** SEEP-IT Student/DOE/NNSA/MSIPP Mentor Panel Discussion for interns at Sandia (Left) and Argonne (Right).



Figure 6. Top: Highlights from the Education/Workforce Development panel discussion on Day 1 led by Prof. Peter Bermel (Purdue University). **Bottom**: Highlights from some of the working group discussions to address the Break-out Questions on Day 1.



Figure 7. Highlights from the poster session involving students and junior scientists sharing their research outcomes. **Bottom Panel-Center and Right**: poster presentations made by STEM Teachers from the Dallas-Fort-Worth (DFW) Metroplex who attended the workshop and shared their findings after an in-house training session hosted within the DOE/NNSA SEEP-IT Teacher Training Institute-University of Texas, Arlington (Lead: Prof. Ann Cavallo).

4.4 Poster Session Awardees



Figure 8. Top Left: Best Postdoctoral Scholar Poster Award presented to Dr. Akshay Wali, Argonne (second from right). **Top Right:** Best Graduate Student Poster Award presented to Thomas Mather, UNT (second from right). **Bottom Left:** Best Undergraduate Student Poster Award presented to Eli Gabaldon, UNT (second from right); **Bottom Right:** Honorable Mention student recognition presented to Candice Smith, UA-PB (second from right). DOE/NNSA/MSIPP Program Manager, Ms. Betsy Snell, shown on far right with the Awardees.

5.0 Working Group Highlights and Summaries

The summary of the presentations by each of the three Working Group Leads and Scribes are listed below in Sections 5.1-5.3, which were featured on Day 2 of the workshop. The formal Working Group Summary Reports for each Working Group were provided by the Leads and Scribes in 2025, with the last formal Working Group Summary Report received in Oct. 2025. These three Working Group Summary Reports were used to compile the Workshop Final Report recommendations, *R1-R7*, delineated in Section 6.0, and disseminated in June 2026.

5.1 Presentation Highlights: Working Group 1

1. *MATERIALS CHARACTERIZATION: What are the core challenges to address in 2D materials property characterization? New characterization tools and approaches, including in-situ techniques for defect characterization, examining light-matter interactions?*

    - Characterization of defects. STM has very good spatial resolution but lacks temporal resolution; RF and THz-STM are rare.
    - Limited availability/understanding of engineered defects/dopants in materials. Quantum qubits suffer from low coherence times since random defects are found at the surface than the bulk.
    - Sample preparation & inspection (ultrathin films) produces unwanted defects; high-energy electron beams may damage the sample.
    - Unlike STM, AFM does not require a conductive sample. However, it is limited by resolution.
    - For quantum emitters, optically detected magnetic resonance (ODMR) and electron paramagnetic resonance (EPR) spin-defects can be utilized measure distribution of spin-centers, e.g. scanning NV microscopy.
    - Understanding the thermal conductivity of materials such as SiC and diamond, particularly for space applications.
    - Understanding transient response in 2D switching transistors with the help of STM
    - New characterization tools and approaches involving light coupling are needed for defect characterization and understanding light-matter interaction.

2. *DEVICE PERFORMANCE: What is needed in the research infrastructure to transform the promise of 2D materials for quantum/photonics/sensors, to an area of scientific and technological strength? Key challenges and translational opportunities device function for 2D materials in quantum, photonics, sensors and CHIPS? Scalability, integration and coupling of 2D materials to photonic and quantum platforms, contacts, doping schemes, substrates, etc.?*

    - Developing scalable, reproducible synthesis methods such as CVD on large substrates and solution-based exfoliation for 2D materials that maintain high material quality and uniformity is crucial.
    - Innovations in low-temperature growth or high-throughput synthesis could make large-scale production viable for industrial applications.

- Developing van der Waals heterostructures that combine 2D materials with other materials, and integration techniques that allow seamless coupling of 2D materials with photonic and quantum platforms.
- Defect engineering and improving material purity (e.g., through annealing techniques, chemical doping, or strain engineering) could help to reduce defects and enhance material properties.
- In situ characterization (e.g., scanning tunneling microscopy, Raman spectroscopy) during material growth and device fabrication will also enable real-time defect detection and control.
- Contact engineering techniques such as the use of metal contacts with optimized work function, graphene electrodes, or van der Waals heterostructures can mitigate contact resistance issues.

3. *AI, THEORY, & MACHINE LEARNING: Accelerating experimental research in 2D materials by leveraging theory, modeling and simulation as a predictive tool for quantum, photonics, sensors, etc. What is the state of the art in publicly accessible materials property database? e.g. Materials Genome Initiative?*

- Accelerating experimental research in 2D materials by leveraging theory, modeling, and simulation as predictive tool for quantum, photonics, sensors, etc.
- AI models can predict properties of new materials such as bandgap, conductivity, stability, and mechanical properties based on their composition and structure.
- Discovery of new materials for good electrical contacts: target NSF-DMREF
- Ability to predict presence of defects / grain boundaries using AI/ML and their impact on device performance.
- Having a state of the art in publicly accessible 2D materials property database such as Materials Genome Initiative for users from across the world.
- ML models can analyze the relationship between synthesis parameters (temperature, pressure, precursor concentration, etc.) for properties optimization of 2D materials.

OTHER COMMENTS / CONSIDERATIONS / GENERAL RECOMMENDATIONS

Increasing awareness thru PI-to-PI discussions (maybe offer lab tours to universities to gain visibility).

Allowing more users from different universities to get hands on experience at different labs. A better engagement with outreach programs is needed.

Collective bottom-up, peer-to-peer dialogue can identify needs of the larger community; help define strategic directions to steer government funding/resources (see “NESC Quantum Sensing CoP”: monthly meeting with different centers and government labs for quantum sensing, discussion about current research, identify overlaps, define needs of this field and where large funding is required.)

5.2 Presentation Highlights: Working Group 2

1. *What are the key areas where 2D materials and devices are expected to make a substantial difference in quantum/photonics/sensors, with respect to existing technologies of interest to government labs/industry?*

Entering market

- Composites
- Point of care biosensors

In industry Roadmaps

- Replacing silicon for GAA FET architectures

Clear strengths but will require infrastructure development/investment

- Hetero-integration with other materials (e.g. diamond, complementary-metal-oxide-semiconductor (CMOS), thin films, metals) for:
  - Power electronics/high voltage electronics
  - Ultrafast electronics, antennas
  - Rad hard electronics
  - Single quantum emitters
  - Quantum sensing
  - Neuromorphic computing

TBD improvement compared with other technologies:

- Wearables
- Quantum for computing

2. What are the needs and potential barriers in global manufacturing of 2D based materials and devices towards photonics, quantum and CHIPS?

- **Scalability**
  - Some applications need CMOS integration first and/or have even higher requirements
    -Quantum computation/sensors
  - Some applications sidestep the high requirements or have orthogonal requirements
    -Biosensors
    -SPE
  - Heterogeneous integration: need to understand the interface interactions and processes
    -Contact engineering in metal/semiconductor interfaces
    -Hysteresis, doping, strain interactions from substrate dielectrics interfaces with 2D-2D
    -Impact on fabrication, characterization, modeling/simulation (3D interfaces a major challenge)

- **Standardization**
    - How to bring single device demonstrations to level needed for technology integration
    - Many demonstrations use unique materials or non-standard processes

- **Optimizing processes to take advantage of interactions, and/or create new processes/tools**
    - Expensive new tool development
      -Transfer with low disorder, low strain, low residue
      -CVD growth at wafer scales, but achieving low enough defect densities still challenging
    - Stability/contamination of interfaces, e.g. in biosensors

- **IP barriers**

3. What collaborative mechanisms are needed for developing innovation ecosystems and translational opportunities that overcome these challenges and the "valley of death" by helping academia engage more effectively with government labs, industry and equipment manufacturers? How are such interactions managed at other locations globally, and is it practical/advantageous to implement such strategies here locally in US (relevant examples of those are Graphene Flagship/European CHIPS Act)?

- Having more dialogue between industry & academia
    - Making great science and deliver to industry, needs to make a business case to industry

- Need funding to develop fundamental knowledge of interfacial interactions
    - Engineering Research Center, SRC, CHIPs, direct industry, EFRC
- Open source technology tools. How to learn about and integrate tools?
    - Nanohub, Process design kit (e.g. Google skywater)
- Pre-arranged IP for suppliers, tool developers, researchers
- Development of standardized platforms for 2D study
    - It is time to start developing 2D foundries
    - Develop new tools when market opportunity
    - National labs have some specific tools, need more
      e.g., Quantum foundry – aim for pure materials for researchers
- Foundries, suppliers, application users
    - Suppliers go to specialty users first, then foundries later

4. *What lessons can we learn from prior research "waves" that will help speed-up R&D of 2D layered materials and devices towards quantum/photonics/sensors and CHIPS?*

- Integrated silicon photonic platforms
    - Integrate many elements all need to be fabricated same way and with similar tools
    - Standardization
    - Need help from nonprofit organizations/national lab

- III-V
    - Timing and inertia and inertia for change important considerations
    - Need to develop and have impact in a timely manner
- Graphene
    - CVD growth matured with time
    - Hype millions invested
    - Just now seeing commercialization (e.g. it takes TIME)
    - Lots of value in fundamental knowledge for material integration
- Diamond NV centers
    - Lots of possibilities for material combinations and defects
    - Coherence strongly related to surface/bulk
- There is not one magic 2D bullet – lots of materials still to be sorted through
- New solutions must make case for enough improvement to justify investment

5.3 Presentation Highlights: Working Group 3

1. *What strategies can improve the recruitment, retention, and preparation of domestic students for careers in semiconductors, 2D materials, and quantum technologies, addressing barriers such as location and type of institution?*

    - Meeting working scientists & engineers
    - Connecting scientists with teachers (see Item 2) and counselors; providing information about current & emerging job opportunities
    - HS release time opportunities
    - Early intervention in math to keep students on track for STEM careers
    - Instilling self-efficacy and belonging for students
    - Monitoring and limiting colluding / cheating
    - Creating tools for success
    - Sharing job opportunities with students
    - Providing role models, including senior scientists, near peers, and parents
    - Raising student, family, and community awareness of opportunities and social benefits
    - Project-based learning opportunities:
        1. Summer programs for students starting early and continuing – immersive, follow-up.
        2. Communicate work-life balance – important to students today. Show the human side of the profession – the fun; the family, friends, social aspects. That it is all achievable.
        3. Enhancing resilience, which is often lacking in today's students – e.g., students drop STEM if they earn a C in their first math course in college
        4. Instilling a growth mindset – effort vs. ability
        5. Retention as important – likely more important than recruitment.
            - **More than half** of students who intend to major in a science or engineering field switch to a different major in college, and this percentage is even higher for community college students.
            - **Students who take fewer STEM classes** their first semester are more likely to switch from STEM majors.

- **The culture of STEM education and potential earnings** in the workplace appear to be significant factors in students' decisions to remain in or abandon STEM majors.

Community Colleges in the Evolving STEM Education Landscape: Summary of a Summit. Washington, DC: The National Academies Press. https://doi.org/10.17226/13399

2. *How can we provide K-12 teachers with knowledge in these areas and incentivize them to teach their students about this, and how can we measure and maximize the impacts on their career choice and readiness?*

    - K-12 teacher summer programs
    - Lab visits and research experiences
    - Field trips
    - Curriculum development: drop in modules to meet standards
    - Poster sessions
    - Inspire student interest: understanding the psychology of how students learn is important – attention; experience; inquiry; chunking information, mental processing
    - Exciting lab demos
    - Follow-up on outcomes & coaching
    - Fair compensation for individual teachers
    - Curriculum alignment within and across HS, CCs, 4-year universities
    - Cross-disciplinary connections
    - Internships & entry courses to try out the field – like UTeach program
    - T-shaped engineer training
    - Equal opportunities for teachers in rural & high need districts
    - University jobs (e.g., lab assistants)

3. *What exchange programs with government labs and industry are effective at all levels (undergrads, grads, and postdocs), and how can we quantify their impacts?*

    - Research at national labs (e.g., SULI, CCI) – preparing students for further studies (e.g., Ph.D. programs)
    - Open House events for general public
    - LANL Practicum (hosted at government labs)
    - Guest speakers at universities
    - Personal recommendations to translate faculty awareness to practical action to help UGs, grads, and postdocs
    - Teaching trainees networking skills (including how to network with faculty)
    - Course on being a good mentee
    - STEM Teacher and Researcher (STAR) program at JPL, Sandia, and Ames Labs

Other Comments/Considerations/General Recommendations

From the National Academies (Bettinger, 2010) five possible reasons for the relative lack of U.S. students pursuing STEM majors in two-year and four-year institutions:

1. At the end of secondary school, few are prepared to enter STEM fields.
2. Few express initial interest in entering STEM fields.
3. Once students are off the STEM pathway, they cannot get back on it.
4. The culture of STEM fields is off-putting once higher education is reached.
5. The returns are insufficiently high to justify greater adherence to STEM fields.

5.4 Working Group 1: Final Summary Report

Discovery-driven research on quantum properties, light-matter interactions, strain, synthesis and scalability

Overview

Working Group 1 focused on discovery-based research in 2D semiconducting materials, particularly as it relates to quantum properties, light-matter interactions, synthesis, strain tuning, and scalability. Discussions were framed around the following themes: A) materials characterization; B) material synthesis, device performance, heterogeneous integration and infrastructure needs; C) integration of Artificial Intelligence (AI)/theory and machine learning (ML) to accelerate materials discovery.

A) Materials Characterization

The following section highlights material characterization techniques that are particularly well suited for studying 2D materials and discusses the challenges associated with their application. An overview of the techniques is shown in **Figure WG1-1**.

One important class of characterization methods relies on scanning probe and electron microscopy techniques, which enable direct spatial imaging of atomic and electronic structures. Scanning tunneling microscopy (STM) is based on measuring the tunneling current between a conductive tip and the sample surface as a function of position and bias voltage. This approach provides access to the local electronic density of states with atomic-scale spatial resolution, allowing detailed visualization of surface defects, dopants, and local band structure variations. However, STM inherently probes only the topmost atomic layers, which leads to difficulties in surface versus bulk defect isolation and also offers limited temporal resolution, complicating the study of dynamic processes.

Transmission electron microscopy (TEM), by contrast, enables direct imaging of the atomic lattice and crystal defects through the transmission of high-energy electrons. This technique provides high structural resolution and can reveal dislocations, grain boundaries, and stacking faults in layered materials. Nevertheless, the high-energy electron beams typically required for TEM often induce damage or alter the sample's structure, especially in delicate 2D materials. Consequently, low-energy and cryogenic TEM variants are increasingly explored to mitigate beam-induced degradation.

Another category of emerging techniques is based on magnetic resonance. The fundamental measurement method in this category is electron paramagnetic resonance (EPR), which is conceptually similar to the more common nuclear magnetic resonance (NMR). While NMR reveals resonances arising from nuclear spin transitions, EPR, as the name suggests, relies on electron spin transitions. Measuring resonant microwave absorption (e.g., 9.4 GHz for X-band) while sweeping an external magnetic field (e.g., around 330 mT for X-band) reveals the energetic structure of the spins. Similar to NMR, the signal intensity fundamentally depends on the Boltzmann distribution (and thus on temperature and the applied magnetic field) as well as on the number of spins involved. This enables quantitative measurements of the concentration of spin

defects and other spin-carrying features in a sample. Key challenges here, are the high number of spins being required to perform EPR, thus a stack of multiple layers of 2D materials is necessary.

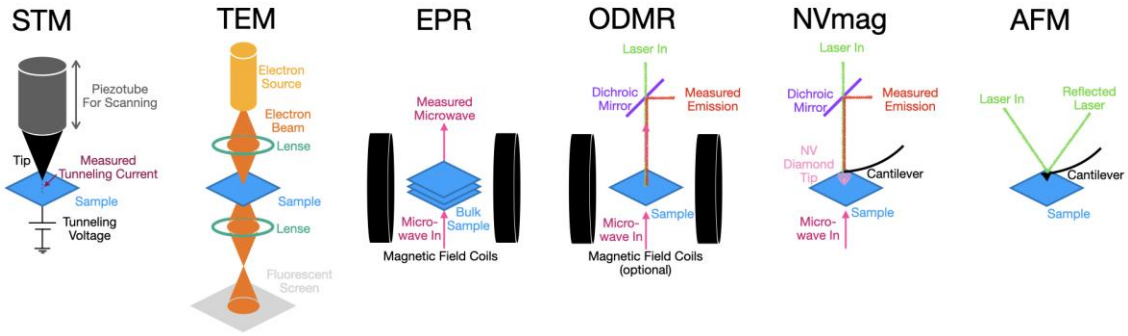


Figure WG1-1. Overview of various material characterization techniques that are particularly well-suited for 2D materials (sample shown in blue). The illustrations provide a simplified depiction of the quantities measured by scanning tunneling microscopy (STM), transmission electron microscopy (TEM), electron paramagnetic resonance (EPR), optically detected magnetic resonance (ODMR), NV magnetometry (NVmag), and atomic force microscopy (AFM).

As color centers are known for their unique optical properties, a particularly powerful complementary technique is optically detected magnetic resonance (ODMR), which combines optical and spin-based measurements. Similar to EPR, spin transitions are induced by resonant microwaves. However, instead of detecting microwave absorption, optical changes, such as variations in the photoluminescence intensity of optically active spin defects, are measured. This approach provides access not only to internal relaxation rates but also to spatially resolved measurements with high precision (diffraction-limited to ~ 1 μm) and even single-spin detection, as demonstrated for NV centers in diamond. It enables detailed insight into the atomic environment of defects by analyzing hyperfine splittings of surrounding nuclei and their isotopes. This technique, however, is only applicable to color centers which show spin-polarization under optical excitation as well as spin-dependent emission.

For 3D materials, ODMR is well established and has further enabled advanced analytic methods such as NV magnetometry (NVmag), where NV centers in 3D materials (or in nanodiamonds, effectively 0D systems) are used to indirectly probe properties of a sample. Because spin defects are highly sensitive to their local environment (e.g., local magnetic fields), localized NV magnetometry can be applied to study the magnetic properties of 2D materials by probing nearby NV centers, either embedded in a diamond substrate or mounted on the tip of an AFM probe. This technique is mostly limited by bringing the probing NV centers sufficiently close to the system under study and by the fabrication of reliable NV-diamond tips. As this technique is still very new, the measurement technique itself remains an active field of research.

In addition to these rather specialized approaches, other more conventional techniques such as atomic force microscopy (AFM) and thermal conductivity methods can be applied, depending on the expected properties of the sample under study. AFM provides a versatile platform to probe surface morphology, local mechanical and electronic properties, and tip–sample interactions with

nanometer resolution. A critical need is identified for non-contact tools with high spatial and temporal resolution to track transient switching dynamics and light–matter coupling, enabling in situ optical mapping of quantum phenomena.

Color Centers as an Example for Discovery-Driven Research in 2D

Advanced characterization techniques have long been essential for identifying functional quantum effects. Color centers emerged as key platforms in 3D materials for quantum applications, with methods such as the aforementioned EPR and ODMR enabling detailed insights into their spin and optical properties. As 2D systems mature, the same methods offer a pathway to uncover and validate new classes of emitters (see **Figure WG1-2** for a rough timeline of discoveries). In 3D materials, the nitrogen-vacancy (NV) center in diamond stands as the most prominent example. Although color centers were recognized decades ago, it was only through advanced characterization techniques that their quantum application potential was revealed.[49] EPR played a central role in identifying spin-carrying defects in bulk, while ODMR provided the crucial link between spin properties and optical emission. Together, these tools enabled NV centers to be established as robust quantum systems, with high brightness, spin-dependent emission, and long coherence times at room-temperature.

Subsequent single-photon emission measurements using Hanbury Brown and Twiss (HBT) interferometry confirmed their suitability for quantum communication. This combination of high-performance properties and reliable characterization not only drove research breakthroughs but also enabled early commercialization and the rise of startups in the quantum domain.[71] Similar methodologies also led to the discovery of other color centers in other materials such as divacancies in silicon carbide (SiC), now an important platform for integrated photonics for quantum communication and quantum interconnects.[72]

This historical arc provides a roadmap for 2D systems. In hexagonal boron nitride (h-BN), the same methodological sequence has already proven fruitful: EPR first confirmed the existence of spin-carrying defects,[73] while ODMR linked their optical signatures to specific spin states (triplet), ultimately identifying the boron vacancy as a key color center.[59] The parallels with NV discovery underscore how systematic application of characterization methods can accelerate defect identification in new materials. Inspired by this discovery also other classes of color centers in 2D materials has been characterized in detail with these techniques, such as carbon-related emission.

The intrinsic surface nature of 2D systems provides additional advantages. Whereas NV centers lose their coherence when brought close to surfaces, limiting their advantage for nanoscale sensing, defects in 2D materials are inherently located within the 2D layers, offering direct coupling to external environments. This opens opportunities in nanoscale nuclear magnetic resonance (NMR) and biological sensing as demonstrated by NV, though challenges in fabrication control and reproducibility must still be addressed.

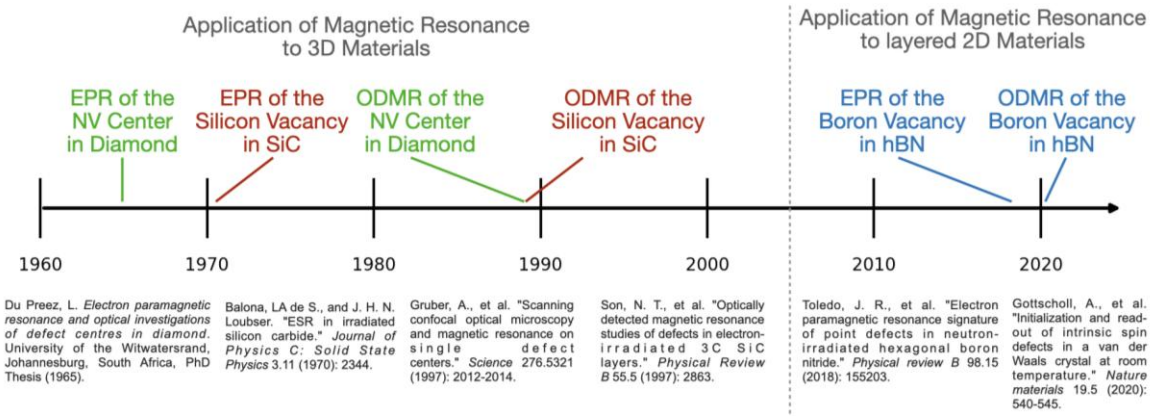


Figure WG1-2. Overview of color center discoveries using magnetic resonance techniques (EPR and ODMR). Applying the same methodologies to 2D materials has enabled the rapid identification of color centers and the development of new applications by building on lessons learned from 3D materials.

B) Material synthesis, device performance, heterogeneous integration and infrastructure needs

Device Performance and Infrastructure Needs

Two-dimensional (2D) materials such as graphene, transition-metal dichalcogenides (MoS_2, WS_2, and WSe_2) have shown tremendous potential for realizing novel devices resulting from their atomic-scale thickness, tunable bandgaps, and exceptional carrier transport properties at the ultimate nanoscale limit.[74,75,76] Three-dimensional (3D) materials, on the other hand, owe their technological prowess to years of intensive research. As such, integrating 2D materials with three-dimensional (3D) surfaces including bulk semiconductors, dielectrics, and metallic interconnects can offer opportunities for high-performance, flexible, and extreme-environment electronics that go beyond conventional complementary-metal-oxide-semiconductor (CMOS) scaling. In light of the potential technological impact, scalable synthesis approaches (e.g., chemical vapor deposition (CVD), exfoliation) and the integration of 2D materials in heterostructures are essential to consider for future advancement. Contact engineering using vdW materials and in situ characterization during synthesis can mitigate defect formation. Infrastructure supporting in situ Raman, STM, and real-time monitoring will greatly aid device uniformity and performance. These topics are discussed further in the subsequent section.

Material Synthesis Challenges

Despite the progress in 2D materials growth, some of the key challenges associated with their full-scale integration are listed below:

a) **Non-uniform coverage and conformality:** 2D materials grown via conventional chemical vapor deposition (CVD) and metal organic CVD (MOCVD) methods often contain wrinkles and non-uniform grain boundaries which severely impact device performance.

b) **Interfacial contamination:** 2D materials are often transferred from their growth to the application substrate. This process introduces several defects and trap states at the 2D/3D interface due to polymer residues which in turn also impact the crystallinity of the transferred material.

Device Performance Considerations

As a result of the limitations described earlier, devices based on 2D/3D integration suffer from the following bottlenecks:

a) **High Contact resistance:** 2D materials-based devices suffer from high contact resistance which severely limits device performance. Therefore, achieving low resistance ohmic contacts is a key challenge for any 2D-based integration scheme.
b) **Device-to-device variation:** The introduction of defects and the random nucleation of grain boundaries and domain walls on any non-2D surface impacts the yield and results in a large device-to-device variation in threshold voltages, on-state current and subthreshold slopes which negatively impacts stability for heterogenous electronics.
c) **Heat dissipation:** For energy-efficient electronics, the presence of 2D materials on the traditional thermally insulating substrates such as SiO_2 and Al_2O_3 results in poor heat dissipation. Here, integrating 2D materials on a thermally active interface such as diamond can help in mitigating this problem and achieve high device current densities.

Heterogeneous Integration and Infrastructural Needs

Despite tremendous advances, realizing 2D/3D integration with stable and reliable operations will require efforts in the following directions:

a) Scalable transfer and direct-growth methods that will preserve crystallinity across large areas on the application substrate.
b) Developing *in*-situ, microscoping and elemental mapping techniques for tracking the electrical and optical properties of 2D/3D heterointerface which will provide insights about various charge transfer phenomenon at the atomistic level.
c) Development of back-end-of-line compatible processes such as low-temperature atomic layer deposition (ALD) growth of dielectrics.
d) Assessing the stability of devices in extreme environment which include exposure to very high temperatures ($> 600℃$) and radiation dosages.

Finally, progress in these areas should aim to bridge the gap between laboratory demonstrations and manufacturable 2D/3D heterostructure systems. This will aid in the development of next-generation of innovative high-temperature logic, radiation-hard cryptographic devices as illustrated in **Figure WG1-3**.

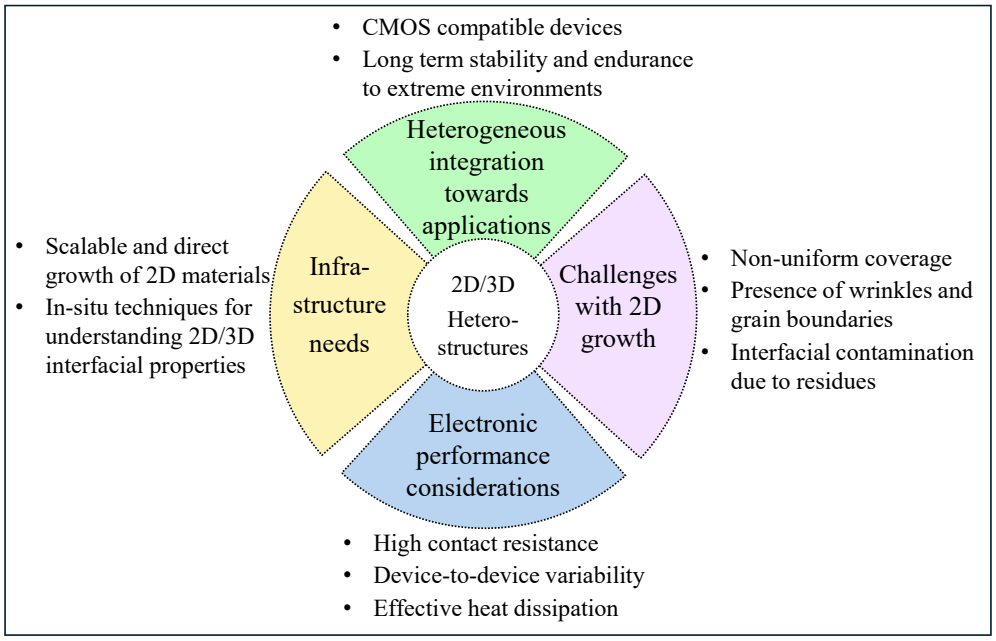


Figure WG1-3. An illustration detailing the challenges for synthesis, device performance in microelectronics, infrastructure needs and heterogeneous integration, including with 2D/3D systems for applications.

C) integration of Artificial Intelligence (AI)/theory and machine learning (ML) to accelerate materials discovery

AI/ML can accelerate discovery by predicting material properties, defect impact, and optimizing synthesis conditions. Integrating large databases (e.g., Materials Project)[77] with experimental feedback loops is a critical path forward. Theory and modeling[78] must be tightly integrated to guide and validate experimental work.

Community and Outreach Considerations

Community engagement and outreach are crucial for advancing discovery in 2D materials and quantum technologies. Broader participation from early-career researchers, university groups, and outreach programs should be prioritized through lab tours, hands-on training, and exposure to emerging tools. Coordination across national labs and academic institutions—such as through the NESC Quantum Sensing Community of Practice—enables alignment on research priorities. Bottom-up, peer-to-peer engagement is also key to identifying knowledge gaps, fostering collaborative networks, and informing strategic proposals for federal funding opportunities.

Recommendations

To accelerate progress, we recommend targeted investments in advanced characterization tools, particularly for defect detection, time-resolved measurements, and probing light-matter interactions. Infrastructure that supports scalable synthesis and integration of 2D materials into photonic and quantum platforms is equally critical. The development of AI/ML tools and open-access databases will further enable experiment-theory co-design. Finally, sustained government support and mechanisms for cross-laboratory collaboration will be essential to translating basic research into real-world applications.

5.5 Working Group 2: Final Summary Report

Innovation ecosystems centered around 2D materials for translational research and alignment with government labs/industry needs towards Quantum/CHIPS

This Working Group 2 report summarizes key insights from a multi-group discussion on the opportunities and challenges in developing an innovation ecosystem centered on 2D materials. The focus was on aligning translational research with the needs of government laboratories, industry, and emerging markets in quantum technologies and the CHIPS Act initiative. The discussion followed four major guiding questions, each addressing a different aspect of the 2D materials innovation landscape.

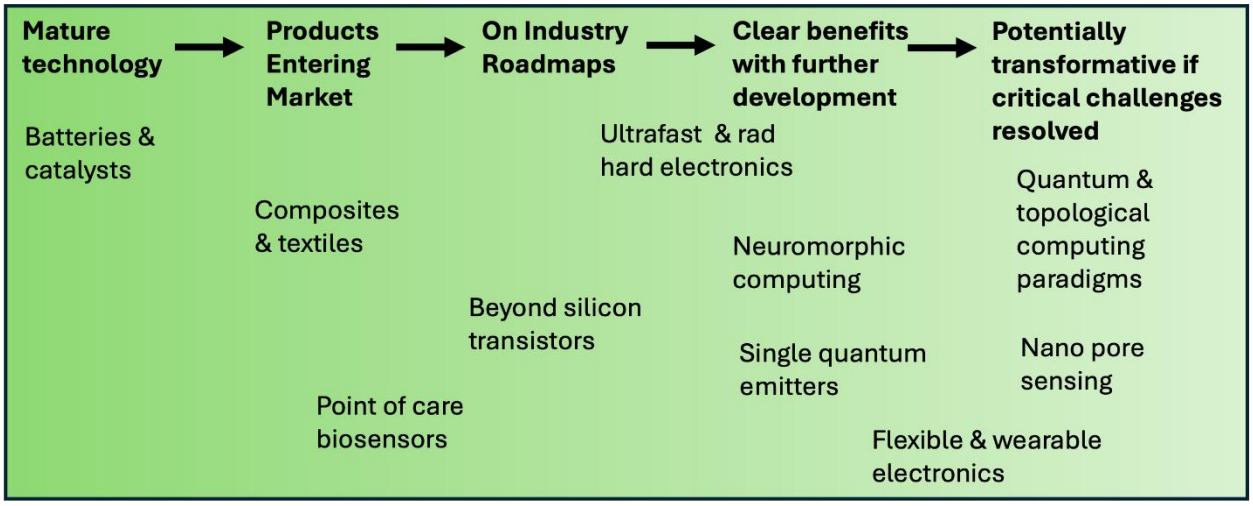


Figure WG2-1. A projection of the 2D materials technology pipeline.

1. What are the key areas where 2D materials and devices are expected to make a substantial difference in quantum/photonics/sensors, with respect to existing technologies of interest to government labs/industry?

Participants identified several domains where 2D materials are expected to make a substantial difference. These domains span various stages in the translational pipeline, from mature technologies, to long-term visionary technologies, as shown in **Figure WG2-1**.

Mature technologies with room for innovation: Layered materials have been an important component in catalysis and batteries. For example, commercial lithium ion batteries typically utilize graphite as a cathode, where the layered structure allows the intercalation of ions. However, the explosion of different layered materials, such as MXenes, TMDs, and black phosphorus has motivated new studies to improve capacity, reactivity or stability, as well as utilize more earth abundant ions for operation.

Products Entering Market: Some 2D materials have recently entered the market, particularly graphene composites found in textiles and construction materials like cement. The incorporation of the 2D material can improve the strength, brittleness, and heat conductivity of the composites, which allows improved performance or less material needed. These applications typically utilize liquid dispersions, where the quality of the 2D material is not a critical factor. Additionally, graphene-based point-of-care diagnostic biosensors are showing early signs of commercialization. Graphene is an atomically thin, which means that any adsorbed molecules effectively electrostatically interact to tune to the conductivity. Because it is a semimetal, the changes in conductivity lead to large and easily measured signals. However, graphene is not inherently selective, where most molecules will impact the conductivity, so there is still a need for development on modifying the graphene surface with different molecule to allow the graphene to selectively respond to different analytes. It is now possible to purchase graphene integrated into point of care sensors such as PH, or potassium, but there is still significant room for improvement. For example, there are demonstrations of selective biomolecule sensitivity down to attomolar concentrations, opening up potential for early disease detection. Longer term there is potential for creating disease assays where arrays of graphene biosensors functionalized with different molecules can do simultaneous testing for many different diseases.

On industry roadmaps: In 2024, all major semiconductor companies have added 2D semiconductors such as MoS_2 and WSe_2 in their roadmaps to replace silicon in gate-all-around (GAA) field-effect transistor (FET) architectures. This declaration represents a major paradigm shift as silicon has been the beating heart of semiconductor electronics for decades. For decades, transistors were built in a planar geometry. Over the last 20 years, transistor architectures have moved into three-dimensions to continuously improve performance, first with ridges to create Fin-FETS, and now in the latest generation with GAA-FET architectures where the channel is made of stacks of silicon nanoribbons a few nanometers thick, with a metal gate surrounding each channel. Looking to the future there are several major reasons why 2D materials are being considered as a replacement. First, the channel layers are now decoupled fully from the substrate, which reduces the reason for using the silicon substrate as the starting material. Second, there is a need to maintain high carrier mobility and current density as device dimensions shrink. However, gating has the strongest impact on the surface of the nanoribbons. Thus, to maximize the current, the silicon nanoribbons need to be made thinner. However, surface scattering effects begin to dominate as the thickness of the nanoribbons drops below a few nanometers, leading to a drastic reduction in performance. For both the electrostatics and property scaling, 2D materials are beneficial. In the monolayer limit, there is no distinction between the material and the surface, so there is maximal efficiency of electrostatic gating. Moreover, 2D semiconductors retain high mobility even at the monolayer limit. Beyond channel materials, there is also growing interest in amorphous 2D materials for dielectrics and doping layers. Finally, both academia and industry routinely demonstrate full wafer growth and transfer of monolayers of the most mature 2D materials such as graphene, or TMDs such as n-type MoS_2 and p-type WSe_2. Though there are still significant improvements that can be made in quality and reproducibility of the material, this shows the realistic potential for manufacturing scale production.

Clear benefits with further development: Additional areas were identified where 2D materials exhibit clear advantages compared with existing approaches but would require substantial infrastructure changes to be fully realized. Many of these technologies require either newer 2D

materials, or require integrating 2D materials into heterostructures or other emerging platforms, and so either need more development from the manufacturing perspective or have even higher requirements than the CMOS applications above. As a result, they will likely become more viable as the more immediate challenges associated with hetero-integration of 2D materials for beyond silicon electronics gets resolved.

First, many 2D materials like MoS_2 exhibit memristive behavior, or have built in multiferroic properties like the ferroelectric alpha-In_2Se_3. Meanwhile, 2D heterostructures of different materials allow strong coupling and gatable tuning of the electronic states with respect to each other all the way down to molecular length scales. As a result, integrating 2D materials into heterostructures has strong potential for low switching energy non-volatile memory, reconfigurable electronics, or neuromorphic computing. Similarly, hetero-integration of 2D materials with other substrates such as diamond, thin films, metals, and flexible polymers opens the door to advances in power electronics, ultrafast transistors, radiation-hardened devices, and wearable electronics.

In addition, many 2D materials exhibit strong light matter interactions. As a result, 2D semiconductors are being explored for use in excitonic and polaritonic solar cells for energy extraction. In addition, because 2D materials are very flexible, they can have intimate contact with photonic systems like waveguides. Yet, simultaneously 2D materials can be gated to modulate their optoelectronic response, allowing new transduction mechanisms for high frequency light modulation or sensing. Finally, single-photon quantum emitters based on 2D materials are particularly promising in quantum sensing applications due to their surface accessibility, offering advantages over bulk-embedded quantum emitters like diamond NV centers.

Potentially transformative if critical problems resolved: For some application areas, 2D materials offer potentially transformative properties, but there are significant challenges or downsides that make it unclear whether these properties can be transferred to technology platforms. For example, while the mechanical flexibility and electronic performance of 2D materials could benefit wearable technologies, their inherent brittleness and complex processing requirements may limit their utility relative to established organic and thin-film alternatives. In nanopore sensing for disease detection and DNA sequencing, 2D materials have atomic-level thickness that could potentially offer single base pair spatial resolution as electrical integration that offers multiplexed measurements. However, challenges like fast translocation speed, noise, and current stability remain which prevent 2D nanopores from achieving actual sensing in mature commercial technologies based on organic nanopores.

Finally, there has been a proliferation of research showcasing exotic quantum and topological states in 2D materials and moiré superlattices, which take advantage of the strong interactions and new symmetries that can only be achieved in these systems. Examples include potential for quantum computing, spintronics, valleytronics, excitonic, and lossless topologically protected states. However, in most of these cases, the same environmental sensitivity that makes 2D materials such great sensors interrupts the coherence of these quantum states which are typically only accessible in ultra-high quality exfoliated materials encapsulated in hexagonal boron nitride dielectrics. Though there has been recent progress on making CVD graphene with the same quality as exfoliated, most current scalable synthesis methods do not have the needed quality, and most CMOS processes induce disorder.

2. What are the needs and potential barriers in global manufacturing of 2D based materials and devices towards photonics, quantum and CHIPS?

A recurring theme across applications is the difficulty of manufacturing 2D materials at the scale and quality required for advanced technologies. Although substantial progress has been made in chemical vapor deposition (CVD) techniques and wafer-scale growth, defect densities in monolayer films remain a persistent obstacle. A large determinant of the position of technologies in the pipeline, as shown in **Figure WG2-1**, is the level of quality of the material needed. Some applications like composites work well with highly defective liquid dispersions of nanoscale flakes of 2D materials. For applications like CMOS integration, achieving uniform, low-defect monolayers with precise doping and strain control is critical, yet extremely challenging with current methods. Some applications, such as quantum computation and neuromorphic computing, will demand even higher levels of material control or more diverse materials than CMOS applications. Therefore, advances in CMOS-compatible 2D integration may serve as a necessary precursor to enabling these next-generation systems. In contrast, other advanced application domains like biosensors or optically addressed devices—such as single-photon emitters—may bypass these stringent requirements. These systems operate in environments or architectures that do not rely on cleanroom integration, allowing for more flexible processing.

The complexity of integrating 2D materials with other components also presents a major barrier. Understanding and engineering interfaces between 2D materials and other thin films or substrates remains an underexplored area. Issues such as contact resistance, hysteresis, doping, and strain induced by substrates can profoundly affect device performance yet are poorly understood. This calls for systematic experimental studies and advanced modeling tools capable of capturing these intricate interactions. There is also an urgent need to develop new fabrication and characterization methods that match the atomic-level control required for reliable integration.

Standardization is another critical bottleneck. While thousands of studies have demonstrated high-performing devices using exfoliated and encapsulated 2D flakes, these approaches are not scalable or repeatable at the level required for industrial manufacturing. To bridge the gap between fundamental research and manufacturable technologies, the field must either adapt existing industrial processes or develop new scalable techniques that preserve the desirable properties of 2D materials. In particular, there is a pressing need to develop scalable encapsulation methods that provide the same level of inert protection and minimal disorder as hexagonal boron nitride.

Another important consideration is the development of tools for the precise manipulation and transfer of 2D layers. Current transfer techniques often introduce mechanical defects, residues, or unwanted strain and doping, compromising material quality. Future tools must enable the integration of 2D films without introducing disorder or contamination. This precision comes at a high cost, and developing these tools will require substantial investment.

Interface stability, both during processing and in operational environments, must also be carefully managed. In CMOS applications, contamination can undermine performance, while in biosensors, post-fabrication molecular interactions with the 2D surface are central to the device's function and must be thoroughly understood.

Finally, intellectual property (IP) barriers represent a systemic challenge to collaborative research. Many companies are pursuing 2D materials internally but cannot easily collaborate due to concerns about data ownership and competitive advantage. Academics often lack the funding to patent their discoveries, while industry sponsors may have access rights but no incentive to fund

patent filings. Another bottleneck is the substantial effort needed to develop manufacturing scale tools for synthesizing and processing 2D materials. There is not yet an industry market and academic institutions do not have the resources to invest in buying, developing or operating these tools, because the output far exceeds what is needed for research groups. Both bottlenecks create a stalemate that impedes progress in tool development, material optimization, and the standardization of processes essential for technology transfer.

3. What lessons can we learn from prior research "waves" that will help speed-up R&D of 2D layered materials and devices towards quantum/photonics/sensors and CHIPS?

Past research efforts offer several instructive lessons for accelerating the translation of 2D materials into viable technologies.

One key example is the fields of integrated silicon photonics and MEMS. In both these technologies the creation of standardized design rules, fabrication protocols, and open-access foundries allowed researchers to build complex devices without needing to master every fabrication step themselves or have access to the most expensive tools. The lesson here is that standardization, supported by nonprofits and national labs, can transform a fragmented research field into a coordinated, scalable ecosystem.

The trajectory of III-V semiconductors offers a cautionary tale. Despite their superior performance to silicon, the inertia of silicon's entrenched infrastructure and the high costs of transitioning to new materials meant that III-Vs never achieved widespread commercial penetration in many sectors. This underscores the importance of timing, coordination, and infrastructure readiness. Even if 2D materials offer superior functionality, their adoption will hinge on the speed with which they can be made compatible with existing or emerging manufacturing platforms.

The development of diamond NV centers for quantum applications highlights the complexity of coherence preservation and the need to understand how material properties shift with surface exposure. These lessons are especially relevant for 2D materials, where surface interactions dominate and coherence may be limited in quantum computing contexts but advantageous in sensing applications.

Graphene, as the first widely studied 2D material, illustrates both the opportunities and the patience required in materials development. Despite intense hype and investment, it has taken nearly two decades for graphene to reach commercialization. Moreover, many of the initially proposed applications, such as nanoribbon transistors did not come to fruition. This is because there is no silver bullet material that will simultaneously solve all problems. Nonetheless, the tools, techniques, and understanding built during this period laid the groundwork for progress in the exploding family of 2D materials. Crucially, this journey shows first that it is critical to take time to explore the fundamental and wildly diverse properties of this class of materials to determine the best candidates for different technologies and second, that at some point, new materials must demonstrate clear added value to justify the significant investment needed for their industrial adoption.

4. What collaborative mechanisms are needed for developing innovation ecosystems and translational opportunities that overcome these challenges and the "valley of death" by helping academia engage more effectively with government labs, industry and equipment manufacturers? How are such interactions managed at other locations globally, and is it practical/advantageous to implement such strategies here locally in US (relevant examples of those are Graphene Flagship/European CHIPS Act)?

To overcome the barriers identified above and bridge the gap between academic discovery and industrial deployment, the 2D materials community must develop new models of collaboration and innovation. Increased and more structured dialogue between industry and academia is essential. Industry leaders must articulate their pain points and unmet needs, while researchers should find ways to translate their fundamental insights to practical use cases.

There is also a pressing need for dedicated funding to deepen our understanding of 2D material interfaces and hetero-integration with CMOS processes. These foundational insights are critical to device reliability and performance but are not currently prioritized in most funding programs, and are more fundamental than the performance focused research in industry. Developing and disseminating open-source design and simulation tools—such as those on platforms like NanoHub or in process design kits like Google's Skywater—can further accelerate knowledge transfer and reduce duplication of effort.

Addressing intellectual property concerns will be central to facilitating cross-sector collaboration. Prearranged IP frameworks, where rights and responsibilities are clearly defined from the outset, could lower legal risks and foster trust between partners, especially in multi-institutional research efforts.

Standardization must also be pursued selectively. While many 2D materials are still in the exploratory stage, a few—such as graphene, MoS_2 and WSe_2—are nearing commercial readiness. These materials could form the basis of standardized platforms or even dedicated 2D foundries, akin to those developed for silicon photonics and MEMS. Several national labs and innovation centers are already investing in 2D growth capabilities, but the next step is enabling full device integration, not just material production.

Developing specialized tools to support these platforms will require coordinated investment and clear market signals. One strategy to break the chicken-and-egg cycle between tool development and standardization is to start with CMOS-focused 2D integration. Success in this area will have downstream benefits for quantum technologies, which often require the same or even greater levels of material and interface control.

In summary, building an effective 2D innovation ecosystem will require a combination of strategic investment, collaborative governance, and technical coordination. By applying lessons from past research waves, addressing manufacturing barriers head-on, and enabling new modes of partnership, the community can accelerate the journey from 2D discovery to impactful deployment in quantum, photonics, and semiconductor technologies.

5.6 Working Group 3: Final Summary Report

Innovations in educational strategies to recruit and prepare a vibrant domestic quantum/CHIPS workforce pipeline

Working Group 3 focused on educational and workforce strategies relevant to the SEEP-IT Consortium and the areas of microelectronics, 2D materials, and quantum more broadly. Its primary work consisted of three specific activities. In Session 4, a series of experts on workforce development presented talks on their experiences and activities in this space. In Session 5, a panel discussion on broadening participation was held. And finally, a dinner-time working group was held to highlight key insights from the prior sessions and augment that with reflections from a wider group of workshop participants, which was then reported back to the group on the following day. Here, recommendations for future work related to Working Group 3 are presented under each Section below.

1. *What strategies can improve the recruitment, retention, and preparation of domestic students for careers in semiconductors, 2D materials, and quantum technologies, addressing barriers such as location and type of institution?*

STEM (Science, Technology, Engineering, and Mathematics) education in the United States faces significant challenges in preparing and retaining students in STEM fields. A major issue begins in high school, where students often lack adequate preparation in mathematics and reasoning skills, particularly in their senior year. Research by Phil Sadler highlights that students who take calculus, a second year of chemistry, or one or two years of physics in high school are significantly more likely to develop an interest in STEM careers.[79] However, many students enter college without this foundation, leading to difficulties in their STEM coursework.

To address these challenges, early exposure to STEM through summer programs is crucial. Programs that begin early and continue with immersive experiences and follow-up support have been shown to foster sustained interest in STEM fields. Additionally, parental involvement plays a critical role in shaping students' academic choices. Engaging parents by communicating opportunities for their children can help reinforce student commitment to STEM education.

One factor that influences students' persistence in STEM is their perception of work-life balance. Modern students value the human aspects of their careers, such as social engagement and personal fulfillment. Highlighting the enjoyable, collaborative, and family-friendly aspects of STEM careers can help retain students. Additionally, mentorship is a crucial component in fostering a sense of belonging. Connecting students with senior or graduate student mentors, as well as young workforce mentors, either in person or through online networks, can provide guidance and support during their academic journey.

Resilience is a major factor in STEM retention. Many students drop STEM majors after earning a C in their first college math course, often perceiving this as a failure rather than a learning experience. Encouraging a growth mindset—emphasizing effort and improvement over innate ability—can help students persist through academic difficulties. Furthermore, self-efficacy and scientific reasoning skills are strong predictors of success in college physics courses and STEM major selection.

Parental support, particularly from fathers, has a notable impact on daughters pursuing STEM fields. Strengthening parental encouragement and involvement can help break gender-based barriers and expand STEM opportunities for underrepresented groups.

Retention is arguably more important than recruitment in addressing STEM workforce shortages. According to a report by the National Academies of Sciences, Engineering, and Medicine,[80] more than half of students who initially intend to major in STEM switch to a different major. The attrition rate is even higher for community college students. Key factors influencing this trend include the number of STEM courses taken in the first semester, the culture of STEM education, and perceived future earnings in STEM careers. Students who take fewer STEM classes in their first semester are more likely to switch majors, underscoring the importance of an engaging and supportive academic environment from the start.

Addressing the challenges in STEM education requires a multi-faceted approach. Strengthening high school preparation, promoting early and continuous engagement, fostering mentorship, emphasizing work-life balance, cultivating resilience, and ensuring parental support can significantly impact student retention. By focusing on these strategies, we can create a more inclusive and sustainable STEM education system that prepares students for successful careers in science and engineering.

2. *How can we provide K-12 teachers with knowledge in these areas and incentivize them to teach their students about this, and how can we measure and maximize the impacts on their career choice and readiness?*

Teacher education programs and teacher summer programs provide in-depth training opportunities, such as Research Experiences for Teachers (RET). These programs can help direct students into STEM fields by fostering partnerships with teacher preparation programs and school districts.

Students often start their STEM majors with enthusiasm but lose interest when early coursework does not align with their future careers. Project-based, experiential learning approaches can enhance student engagement by making coursework more relevant. Understanding how students learn—through attention, experience, inquiry, chunking information, and mental processing—can improve teaching effectiveness.

Providing an entry-level course that allows students to explore STEM fields—similar to the UTeach program—can be beneficial. Hands-on lab experiences or summer internships can help students understand what the field entails. Offering scholarships for students who stay in STEM, along with continued field and laboratory experiences integrated into their coursework, has proven effective. For instance, the UTeach program at the University of Texas at Arlington, supported by Noyce, increased its STEM teacher graduates from five to fifty per year and successfully graduated a higher percentage of students from varying backgrounds than the university's overall student demographic percentage.

Creating a replicable, standardized program and sharing best practices among institutions can further strengthen STEM education. Conferences that bring students together to discuss common curricula and courses can facilitate knowledge exchange and collaboration. Additionally, scientists should actively engage in STEM teacher education programs, contributing their expertise to the broader STEM teacher education community.

3. *What exchange programs with government labs and industry are effective at all levels (undergrads, grads, and postdocs), and how can we quantify their impacts?*

Exchange programs with government labs and industry provide invaluable opportunities for undergraduates, graduate students, and postdoctoral researchers to gain hands-on experience, develop professional networks, and contribute to cutting-edge research. These programs foster collaboration between academia and industry, bridging the gap between theoretical knowledge and practical application. Several key programs have proven effective in engaging students and researchers at various levels.

The National Science Foundation (NSF) Research Experiences for Teachers (RET) program plays a crucial role in equipping educators with real-world research experience. By embedding teachers in government and industry labs, the program enhances STEM education at the K-12 level. Teachers bring their experiences back to the classroom, inspiring students with firsthand knowledge of scientific inquiry and industrial applications. This approach creates a ripple effect, encouraging more students to pursue STEM careers.

STEM summer programs for high school students provide early exposure to research and industry practices. Sustained programs that incorporate mentorship, hands-on projects, and internships create long-term engagement. Students who participate in such programs develop a deeper understanding of STEM fields and gain confidence in their ability to pursue technical careers. Industry partnerships ensure that these programs remain relevant, incorporating emerging technologies and addressing workforce needs.

Internships with government labs and industry for undergraduate and graduate students are essential for skill development and career readiness. These opportunities allow students to work alongside experienced professionals on real-world projects, fostering critical thinking and problem-solving abilities. Follow-up initiatives, such as continued mentorship and networking events, help students transition into the workforce or advanced studies. Structured internships, such as those offered by the Department of Energy's national labs or NASA's research centers, have been particularly successful in training the next generation of scientists and engineers.

Postdoctoral research exchanges between academia, government labs, and industry facilitate the transfer of knowledge and innovative solutions. These programs support advanced research while also preparing postdocs for careers in both academia and industry. Collaborative initiatives such as the NSF's Postdoctoral Fellowship Program and industry-sponsored research fellowships enable postdocs to gain interdisciplinary experience, broadening their career prospects.

Quantifying the impact of these exchange programs requires systematic tracking and assessment. Metrics such as program retention rates, subsequent STEM degree attainment, workforce placement, and long-term career outcomes provide insight into their effectiveness. Longitudinal studies that follow participants over time, as well as qualitative feedback from alumni and employers, contribute to a comprehensive evaluation. Additionally, industry and government partnerships can provide data on the success of program graduates in addressing workforce needs. By expanding and refining these exchange programs, stakeholders can ensure that students and researchers receive meaningful, career-enhancing experiences that drive innovation and strengthen the STEM pipeline.

6.0 Final Recommendations from Workshop

This *SEEP-IT National Workshop on 2D Semiconducting Layered Materials Towards Quantum, Photonics, and Microelectronics to Fuel Innovations and Workforce Development* presented a unique forum to bring together leading researchers from academia, government and industry to discuss the challenges and opportunities at the intersection of various domains. The topics discussed spanned basic science, particularly as it relates to quantum effects in 2DLMs, to more applied areas involving the integration of 2D semiconductors into microelectronics platforms. These parallel directions for fundamental scientific studies to address the technical challenges, and their lab-to-fab pathways for translational applications should mirror the funding models available to the community for sustainable innovations and progress. Single-PI or few-PI efforts are ideally positioned to address key focused scientific questions, while larger interdisciplinary team efforts are an effective means to tackle translational complex technological bottlenecks. Through the Working Group discussions, it was clear that building an effective 2D innovation ecosystem, particularly as it relates to 2D-based microelectronics and semiconductor manufacturing in the US will require a combination of strategic investment, collaborative governance, and technical coordination. By applying lessons from past research waves, addressing scalability barriers head-on, and enabling new modes of partnership, the community can accelerate the journey from 2D discovery to impactful deployment in quantum, photonics, and semiconductor technologies. The recommendations from the three Working Groups provide valuable insights into each domain, where the seven cross-cutting recommendations, *R1-R7* below from this workshop final report, can serve as a guide to future funding programs central to 2D semiconductors and workforce development efforts, as they align with important national needs and initiatives.

R1. Expanding Infrastructure for Quantum Science for Defect Characterization and Techniques

The participants discussed that basic science funding will remain vital to continue building the fundamental understanding and knowledge on the structure-property correlations between defects in 2D semiconductors and their photonic emission properties towards QIS and technology. To accelerate progress, it was recommended that targeted investments be made in advanced characterization tools, particularly for defect detection, time-resolved measurements, and probing light-matter interactions, building upon well-established surface science techniques. As an example, besides scanning probe and electron microscopy for direct spatial imaging of atomic and electronic structures, STM is available for accessing the local electronic density of states with atomic-scale spatial resolution. This allows detailed visualization of surface defects, dopants, and local band structure variations. However, STM inherently probes only the top-most atomic layers, which leads to difficulties in surface versus bulk defect isolation and also offers limited temporal resolution, complicating the study of dynamic processes. Advancement in characterization tools and techniques based on magnetic resonance such as electron paramagnetic resonance (EPR) can be further developed, but as color centers are known for their unique optical properties, a particularly powerful complementary technique is optically detected magnetic resonance (ODMR). This combines optical and spin-based measurements as well as nitrogen-vacancy (NV) magnetometry used for quantum sensing. Further advancement in these highly sophisticated techniques will benefit from more resources being allocated for instrumentation and infrastructure development, as well as expanding mechanisms for their access by the broader scientific community.

R2. Expanding Theory-driven Research with the Use of Artificial Intelligence (AI) and Machine Learning (ML) for Quantum and Microelectronics

AI and ML can play an important role in predicting the properties of new structural defects in atomic layered materials, and to probe structure-property correlations towards quantum emission, as well as simulating synthetic growth processes. The development and dissemination of open-source design and simulation tools, such as those available on NanoHub or in process design kits like Google's Skywater, can further accelerate progress, reduce duplication of efforts and save costs by targeted experiments informed by theory. These AI/ML tools can predict material properties, defect impact, and optimize synthesis conditions, to accelerate discovery-based research, by both guiding and validating the experimental work. Integrating large databases (e.g., Materials Project) with experimental feedback loops is a critical path forward, and AI/ML tools coupled with open-access databases will further enable experiment-theory co-design. It is recommended more resources for small group projects are made available, involving an interdisciplinary team of computational materials design theorists working in concert with experimentalists (e.g., chemists, materials scientists, physicists, electrical and optical device engineers, etc.).

R3. Promoting Research on Scalable 2D Materials Synthesis, Hetero-interfaces, Standardization, and Tool Development for Microelectronics

While thousands of studies have demonstrated high-performance devices using small area (5-100 μm linear dimensions) exfoliated and encapsulated 2D flakes, these approaches are not scalable or repeatable at the level required for their translational use. Scalability and reproducibility of high-crystalline quality 2DLMs still needs further development to overcome key issues. Challenges of paramount importance include understanding growth mechanisms for uniform, controllable, single crystal formation of 2DLMs over large areas laterally and in vertical stacks, including the incorporation of 2D dielectrics, controlling layer number, doping uniformity and reducing contact resistance. Here, the main points of *R3* are captured within the context of (i) and (ii) below.

i. Hetero-interfaces including compatibility with 2D-3D CMOS integration

Supporting research in heterostructures is clearly a critical area and the gap needs to be bridged between laboratory demonstrations and manufacturable heterostructure systems, including CMOS compatible 2D-3D heterostructures for sensors, extreme environment high-temperature logic, and radiation-hard cryptographic devices, as a few examples. The complexity of integrating 2DLMs with other components presents a major barrier which may require the development of low-temperature processes for back-end-of-line integration using techniques such as atomic layer deposition (ALD) for the growth of dielectrics and other materials. The participants discussed that there is a pressing need for dedicated funding to deepen the understanding of 2DLM interfaces and hetero-integration with CMOS processes. These foundational insights are critical to device reliability and performance, but are currently not prioritized in most funding programs, and are more fundamental than the performance focused research in industry. Understanding and engineering interfaces between 2DLMs and other thin films or substrates remains an underexplored area. Issues such as contact resistance, hysteresis, doping, and strain induced by substrates can profoundly affect device performance and yet that is poorly understood, calling for systematic experimental studies. Interface stability, both during processing and in operational environments, must also be carefully managed. In CMOS applications, contamination can

undermine performance, while in biosensors, post-fabrication molecular interactions with the 2D surface are central to the device's function and must be thoroughly understood. These bottlenecks can be addressed through new initiatives to fund single- or few-PI efforts for focused programs, as well as larger team center efforts composed of interdisciplinary experts.

ii. Tool development, standardization and scalability

While large-area, direct-growth approaches are well-founded avenues for further development, scalable transfer methods that preserve crystallinity across large areas on the application substrate are critically needed. Investments that address tool development for scalable transfer and encapsulation, similar to h-BN's passivating role, would be a step towards the standardization of devices. By using more mature and well-studied 2DLMs such as MoS_2 and WSe_2, these may then help simplify the subset of materials for tackling standardization selectively. Such selective approaches may even lead to dedicated 2D foundries, akin to those developed for silicon photonics or micro-electro-mechanical-systems (MEMS). Several national labs and innovation centers in the US are already investing in 2D growth capabilities, but the next step is enabling full device integration, not just material production. To bridge the gap between fundamental research and manufacturable technologies, tools need to be developed for the precise manipulation and transfer of 2D layers which will require substantial investment. On the microelectronics side, one strategy between tool development and standardization is to start with CMOS-focused 2D integration. Success in this area will have downstream benefits for quantum technologies, which often require the same or even greater levels of material and interface control.

Tool development in the context of *in*-situ microscopy and elemental mapping was also discussed to track the electronic and optical properties of heterointerfaces which will provide valuable insights into charge transfer phenomena within the device at the atomistic level. Additionally, while large scale nanomanufacturing efforts exist internationally in Europe through the Graphene Flagship and others in Australia, China, and the Pacific Rim, the US will benefit from strengthening efforts in this area through well-orchestrated coordination. This may include the need for a prototyping facility where researchers from academia and small businesses are given priority to explore 2D material and device fabrication runs, which are often prohibitive at commercial fabrication facilities due to cost, inflexible schedules, and concerns over contamination. Thus, establishing a prototyping facility at regional locations nationally may provide a low-cost, high flexibility option for testing designs, materials, and processes, and is a segway to *R4*, discussed next.

R4. Promoting Mechanisms for Academia-Government-Industry Collaborations to Address Bottlenecks

There was consensus at the workshop that aligning translational research with the needs of government laboratories, including the DOE, industry, and emerging markets in quantum technologies and CHIPS-focused industries should take priority. Sustained government support and mechanisms for cross-laboratory collaboration will be essential in translating basic research into real-world applications through innovation ecosystems centered around 2DLMs. Thus, the creation of academia-government-industry axes will be vital in establishing stronger connections between basic science explorations, nanomanufacturing initiatives, and industry to help address some of the bottlenecks with 2DLMs towards applications and subsequent commercialization. Such programs may be facilitated through strategic coordination with national manufacturing pilot plants involving the DOE or other government entities. As an example, within *R3*, a major

bottleneck is the substantial effort needed to develop manufacturing scale tools for synthesizing and processing 2DLMs. There is not yet an industry market, and academic institutions do not have the resources to invest in buying, developing or operating these tools, because the output far exceeds what is needed for research groups. Both bottlenecks create a stalemate that impedes progress in tool development, material optimization, and the standardization of processes essential for technology transfer.

Thus, increased and more structured dialogue between industry, academia and government labs is essential. To overcome the barriers identified and bridge the gap between academic discovery and industrial deployment, the 2DLMs community must develop new models of collaboration and innovation, facilitated via public-private-government funding initiatives. Funding large center-like efforts, co-sponsored by multiple agencies and industry will help bridge the "*valley-of-death*" to ensure translation of device prototypes to a manufacturing technology. A public-private research and development consortium or center involving 2DLMs, similar to DOE's Advanced Manufacturing Office (AMO) PowerAmerica model, maybe an avenue to bring together academic researchers, industry and government labs under one umbrella to create a collaborative community with shared common goals. Industry can set meaningful metrics for benchmarking, with a roadmap for the technologies to be developed, where direct input from industry is critical to justify the directions being pursued.

A practical concern in this regard is Intellectual Property (IP) which is a systemic challenge in fostering collaborative research between academia, government labs and industry. Many companies are pursuing 2DLMs internally but cannot easily collaborate due to concerns about data ownership and competitive advantage. Academics often lack the funding to patent their discoveries, while industry sponsors may have access rights but no incentive to fund patent filings. Addressing IP concerns is central to facilitating cross-sector collaborations. It was discussed that pre-arranged IP frameworks, where rights and responsibilities are clearly defined from the outset, be established to lower legal risks to foster trust between partners, especially in multi-institutional research efforts.

R5. Amplifying Mechanisms for Exchange Programs with Government Labs and Industry for Workforce Development

Exchange programs with government labs and industry provide invaluable opportunities for researchers (e.g., faculty fellows, postdoctoral scholars, graduate students, and undergraduates) to gain hands-on experience, develop professional networks, and contribute to cutting-edge research. These programs foster collaboration between academia, government labs and industry to bridge the gap between theoretical knowledge and practical application. As one example, postdoctoral research exchanges between academia, government labs, and industry facilitate the transfer of knowledge and innovative solutions, while preparing postdocs for careers in both academia and industry. Internships with government labs and industry for undergraduate and graduate students are essential for skill development and career readiness. These opportunities allow students to work alongside experienced professionals on real-world projects, fostering critical thinking and problem-solving abilities. Follow-up initiatives, such as continued mentorship and networking events help students transition into the workforce or pursue advanced studies. Structured internships, such as those offered by the DOE national labs through the Science Undergraduate Laboratory Internships (SULI), Navy's Naval Research Enterprise Internship Program (NRIEP), or NASA's Pathways Internships, have been particularly successful in training the next generation of scientists and engineers. In this regard, the DOE/NNSA/MSIPP program has provided

invaluable opportunities to students, where a multi-pronged approach is used to train students at all levels through collaboration networks with the DOE/NNSA labs, such as Sandia and Argonne within the SEEP-IT Consortium. By expanding and refining these exchange programs, stakeholders can ensure that students and researchers receive meaningful, career-enhancing experiences that drive innovation and strengthen the US STEM workforce pipeline, particularly in the areas discussed at this workshop, related to quantum sciences and technology, as well as semiconductors and microelectronics.

R6. Strengthening Efforts to Infuse Quantum and Microelectronics Concepts into the Educational Curriculum for STEM Recruitment and Talent Retention

A central issue discussed at the workshop was the challenge in recruiting and retaining students in STEM educational pathways which directly translates to the workforce development pipeline. Students often start their STEM majors with enthusiasm but lose interest when early coursework does not align with their future careers. In the topical areas of this workshop pertaining to quantum, semiconductors and microelectronics, innovations in STEM education are needed using a multi-faceted approach to attract students into these domains through intentional directed mechanisms and messaging. Students graduating from high school often gravitate towards sectors such as software, AI, as well as finance, given their typically larger starting salaries. This competition makes it increasingly difficult to attract incoming undergraduate students into semiconductors and hardware-related trajectories. Thus, coursework and messaging must be modified so that incoming undergraduates are made more aware of the exciting opportunities available to them within these domains in order to recruit the best talent. Starting outreach far earlier in the K-12 years to increase awareness and interest in quantum, semiconductors and microelectronics is needed, similar to the transformation in student perspectives that has taken place in fields such as robotics, computer science and the software realm.

In this regard, the University of Chicago has launched pioneering degree programs in quantum engineering, which is amongst the first in the nation. Bringing these educational initiatives to the forefront will be important to emulate best practices and lessons learned at other regional locations throughout the US. Through the discussions at the workshop, perspectives on engaging talent from wide student population sectors in R1 and non-R1 institutions was discussed by involving faculty mentors and national labs mentors who are experts in these domains. Just as in regular STEM-topics, project-based and experiential learning approaches can enhance student engagement by making coursework more relevant. Understanding how students learn, through attention, experience, inquiry, chunking information, and mental processing, will improve teaching effectiveness. Providing an entry-level course in the topical area of quantum and microelectronics will allow students to explore these areas, coupled with hands-on lab experiences or summer internships so students better understand what the field entails.

Participants also discussed that scientists should actively engage in STEM teacher education programs, contributing their expertise to the broader STEM teacher education community (e.g. SEEP-IT Consortium's Teacher Training Program-UTA). Teacher education programs and teacher summer programs, as they relate to the emerging topics of quantum and microelectronics, will provide in-depth training opportunities to help direct students into these fields by fostering partnerships with teacher preparation programs and school districts. By embedding teachers in government and industry labs, the program will enhance STEM education at the K-12 level. Teachers will bring their experiences back to the classroom, inspiring students with firsthand

knowledge of scientific inquiry, and current technological trends in government and industry. This approach creates a ripple effect, encouraging more students to pursue the topical areas, amplifying their STEM careers more broadly. Offering scholarships for students who stay in STEM, and within these topical areas, along with continued field and laboratory experiences integrated into their coursework should be used, given their proven effectiveness.

R7. Amplifying the Quantum/Microelectronics/STEM Education Pipeline through Community Engagement and Outreach

It was very obvious from the workshop that the community currently engaged in the research areas discussed is very eager to enhance outreach efforts to the younger generation, their teachers, and the public to improve societal awareness. Community engagement and outreach are crucial for advancing discovery in 2DLMs as it relates to quantum, semiconductors and semiconductor manufacturing. One factor that generally influences students' persistence in STEM is their perception of a work-life balance. The current generation of students value social engagement and personal fulfillment as being directly interwoven with the human aspects of their careers. Bringing the collegial, enjoyable, and family-friendly aspects of STEM careers to the forefront, can help with retention of the modern generation of students. Additionally, mentorship is a crucial component in fostering a sense of belonging. Connecting students with senior or graduate student mentors, as well as early career mentors in government labs and industry, either in person or virtually, can help them identify with a supportive network during their academic journey. Programs that begin early and continue with immersive experiences and follow-up support, have been shown to foster sustained interest in the STEM fields. Additionally, parental involvement plays a critical role in shaping students' academic choices. Engaging parents by communicating opportunities for their children can help reinforce student commitment to STEM education. Sustained programs that incorporate mentorship, hands-on projects, and internships create long-term engagement. Students who participate in such programs develop a deeper understanding of the STEM fields and gain confidence in their ability to pursue technical careers. Industry partnerships ensure that these programs remain relevant, incorporating emerging technologies and addressing workforce needs. Strengthening high school preparation, promoting early and continuous engagement, fostering mentorship, emphasizing a work-life balance, cultivating resilience, and ensuring parental support can all work synergistically to significantly improve student retention.

Conclusion and Acknowledgements

In conclusion, the research presentations, panel discussions, poster session discussions, and working group discussions were in alignment to address the goals of this workshop. We would once again like to thank all the invited speakers, panelists, working group Leads and Scribes, organizing committee members, and guests for their participation and valuable contributions at this workshop to make it a successful event, carried out under the DOE/NNSA/MSIPP SEEP-IT Consortium (DE-NA0004114).

7.0 Abstracts Book (participants)

Kawtar Hafidi

Associate Laboratory Director, Physical Sciences and Engineering,
Argonne National Laboratory

BIO: Dr. Kawtar Hafidi is Associate Laboratory Director for the Physical Sciences and Engineering directorate at Argonne National Laboratory. She oversees five Argonne research divisions and two U.S. Department of Energy (DOE) user facilities conducting fundamental and applied research in nuclear and high energy physics, materials science, chemical science and engineering, and nanoscience and technology. During her 21 years of experience in leading and conducting fundamental research at major accelerator facilities in the United States and Europe, she has distinguished herself as a scientific leader. Before assuming the role of Associate Laboratory Director, she served as the director of Argonne's Physics Division, where she established Argonne as an isotope producer lab and established the Argonne Trace Radioisotope Analysis Center (TRACER), a new, permanent home for the nation's only laser-based krypton atom-counting machine. Previously, as the laboratory's Associate Chief Scientist for Laboratory-Directed Research & Development (LDRD), Hafidi established processes aimed at supporting Argonne's most important scientific priorities and assuring the greatest possible return on early scientific investment. From 2013 to 2014, Hafidi was detailed to DOE's Office of Nuclear Physics, where she demonstrated her ability to forge strong relationships within the U.S. physics community while managing a suite of major projects devoted to achieving America's scientific missions in physics. She received her PhD in Nuclear Physics from Paris XI University, Orsay, France. Her research has focused on the experimental study of quantum chromodynamics in the strong régime, with emphasis on nucleon form factors, flavor decomposition, spin structure, and transverse momentum dependent distributions. She is the author of more than 200 publications and has given more than 60 invited talks at international conferences, universities and laboratories. Hafidi has completed Argonne's highly selective Strategic Laboratory Leadership Program, a non-degree executive leadership program at the University of Chicago's Booth School of Business. She has also received extensive management and leadership education and training through the American Physical Society and the Association of Women in Science. Hafidi has been recognized for her many scientific accomplishments, including her recent nomination as a Fellow of the American Physical Society. She has also been a recipient of the Argonne Women in Science and Technology Diversity Award, UChicago Argonne LLC Pinnacle of Education Award, American Women in Science Innovator Award, U.S. Department of Energy's Office of Science Outstanding Mentor Award, and Commissariat à L'Énergie Atomique Graduate Research Excellence Fellowship.

Betsy Snell

Program Manager, Department of Energy (DOE), National Nuclear Security Agency (NNSA),
Minority Serving Institution Partnership Program (MSIPP)

BIO: Betsy Snell is the Federal Program Manager for the Minority Serving Institution Partnership Program (MSIPP) and the Tribal Education Partnership Program (TEPP) in the National Nuclear Security Administration. In this role, Snell is responsible for the administration and management of a multi-million-dollar federal portfolio, in addition to monitoring expenditures and analyzing program impact. Betsy has over 19 years of grants management experience with the Federal Government, with previous roles in systems policy, program development and analysis and financial administration of funding to a variety of recipients through grants, cooperative agreements, contracts and other transactions.

Argonne's Microelectronics Initiative

Amanda Petford-Long
Argonne National Laboratory

Abstract

Argonne's Microelectronics strategy uses a co-design approach and is focusing on two areas that are aligned with improving energy efficiency:

- Discover new architectures, materials and phenomena for energy-efficient AI-based computing while reducing use of critical materials
- Creating new approaches to reducing the environmental impact of microelectronics manufacturing.

Argonne has established the Argonne Microelectronics Institute (AMI) in order to strengthen the collaboration among our internal microelectronics research programs and help grow their capabilities, and to serve as first point of contact for external partners who wish to work with Argonne. Our expertise, capabilities, and user facilities are critical to our strategy, as is the use of AI and autonomous discovery tools to speed our innovation. I will discuss some of Argonne's capabilities and present highlights of some of our projects.

BIO: Dr. Amanda Petford-Long is an Argonne Distinguished Fellow in the Materials Science Division (MSD) at Argonne National Laboratory in Chicago. In addition to her own research program, she serves as the Division Director of MSD and the Director of Argonne's Microelectronics Institute. She has a D.Phil. (PhD) in Materials Science from the University of Oxford and a B.Sc. in Physics from University College, London. She moved to Argonne in 2005 from the University of Oxford where she was a full professor in the Materials Department. Her research focuses on nanomaterials and a particular emphasis is on magnetic and resistive-switching nanostructures with potential applications in information storage technology, and on the use of in-situ TEM. She has published over 360 scientific papers. She is a Fellow of the Royal Academy of Engineering, the Royal Microscopical Society, the American Physical Society, and the Materials Research Society, and is a Professor in the Materials Science and Engineering Department at Northwestern University

Quantum Simulations for Quantum Technologies

Giulia Galli
University of Chicago & Argonne National Laboratory

Abstract

Which materials are best suited to harness the power of coherent quantum states for quantum applications, including computing, sensing, and communication? Can we predict their physical properties through theory and computation? Can we identify strategies and design rules to synthetize materials with controllable 'quantum' noise? I will address these questions for a specific platform for quantum technologies: spin defects in semiconductors and insulators. Electron spins can provide controllable qubits with long relaxation and coherence times, and they can be coupled to nuclear spins for long-lived quantum memories. I will present results of quantum simulations on hybrid quantum-classical architectures for three and two-dimensional solids and illustrate strategies to integrate theory, computation, and experiments.

BIO: Dr. Giulia Galli is the Liew Family Professor of Electronic Structure and Simulations in the Pritzker School of Molecular Engineering and the Department of Chemistry at the University of Chicago. She also holds a senior scientist position at Argonne National Laboratory, where she is a group leader and the director of the Midwest Integrated Center for Computational Materials. She is an expert in the development of theoretical and computational methods to predict and engineer material and molecular properties from first principles. Her research focuses on problems relevant to the development of sustainable energy sources and quantum technologies. Prior to joining UChicago, she was professor of chemistry and physics at the University of California, Davis (2005-2013) and the head of the Quantum Simulations group at the Lawrence Livermore National Laboratory (LLNL, 1998-2005). She holds a PhD in Physics from the International School of Advanced Studies in Trieste, Italy. She is a member of the National Academy of Sciences, the American Academy of Arts and Science, and the International Academy of Quantum Molecular Science, as well as a fellow of the American Physical Society and the American Association for the Advancement of Science. She is the recipient of several awards, including the Materials Research Society Theory Award, the American Physical Society David Adler Award in Materials Physics, the Feynman Nanotechnology Prize in Theory, the medal of the Schola Physica Romana and the Tomassoni-Chisesi award by La Sapienza University in Rome, Italy.

Understanding and Controlling Defects in 2D Materials on Atomic Length Scales for Quantum Information Science

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Abstract

Point defects in three-dimensional (3D) crystalline system can exhibit optical activity and addressability and long spin coherence times, and therefore are of key interest for quantum information science (QIS) and nanoscale sensing applications. The controlled positioning of these point defects within the bulk crystal, however, is an outstanding challenge. The two-dimensional (2D) system provides multiple advantages over the 3D system, including heterostructure engineering, reduced sensitivity to nuclear spin environment, easier access for nanoscale sensing, and simplicity of integration with photonic platforms. In this context, 2D transition metal dichalcogenides (TMDs) and hBN offer extensive functionality and tunability, particularly in the generation and manipulation of solid-state point defects. In addition to intrinsic defects, various techniques, including focused ion beam application [1] and ultraviolet (UV) light irradiation [2], can efficiently create defects in TMDs. Furthermore, introduction of dopants for tailored optical and spin properties is possible [3,4]. However, atomic-scale visualization and control of defects and dopants remains extremely challenging.

To address this shortcoming, we are developing the Atomic Quantum Information Surface Science (AQuISS) Lab at the Center of Nanoscale Materials (CNM) at Argonne, with the goal of combining the techniques of ultrahigh vacuum (UHV) surface science and scanning probe microscopy (SPM) characterization with quantum spectroscopy and control. Our approach includes developing a 4K UHV STM/qplus AFM with integrated optical and RF access to characterize, improve, and control defects and dopants near and at surfaces. We will outline this approach and our progress on the instrumentation. We will also discuss early efforts to explore defects in bilayer WSe_2 and single-layer MoS_2, showing how we can image atomic-scale structure, identify the local quantum states, and control the charge state at individual defects [5].

References:

1. M. Elmar. *et al. Nano Lett.* 2020, 20, 6, 4437–4444.
2. W. Wang, *et al. ACS Nano* 2022, 16, 12, 21240–21247.
3. J. Y. Tsai, *et al. Nat. Commun.* 2022, 13, 492.
4. J. C. Thomas, *et al. Nat. Commun.* 2024, 15, 3556.
5. R. Zhang, *et al.*, *J. Phys. Chem. C* 2021, 125, 14056.

BIO: Dr. Jeff Guest is a scientist in and group leader of the Nanoscale Synthesis and Characterization group at the Center for Nanoscale Materials at Argonne National Laboratory. He obtained his Ph.D. in Applied Physics from the University of Michigan where he built a 4K near-field scanning optical microscope to study quantum coherence of single quantum dots under the guidance of Prof. Duncan Steel. In postdoctoral work at the University of Michigan and Argonne National Laboratory, Dr. Guest developed laser-cooling and trapping methods to study cold atoms in experiments from cold plasma physics to time-reversal tests. At the Center for Nanoscale Materials, Dr. Guest explores electronic, magnetic, optical properties of matter on nanometer length scales using low temperature ultrahigh vacuum scanning probe microscopy and 'single particle' laser spectroscopy and microscopy techniques, targeting systems such as

single atoms and molecules, self-assembled molecular heterojunctions, photocatalytic surfaces, and quantum defects in 2D materials. He also studies and develops new ways of measuring and controlling mechanical motion of nanofabricated and self-assembled nanoscale systems

Optical Accessible Spin Defects in Hexagonal Boron Nitride: Identification, Control and Application of the Negatively Charged Boron Vacancy

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Abstract

Spin defects in solid-state materials have immense potential in quantum information technology and sensing applications. This talk will focus on a novel spin defect that was recently discovered in a graphene-like van der Waals material: the negatively charged boron vacancy in hexagonal boron nitride. This system possesses a spin-triplet ground state with spin-dependent photoluminescence, enabling an optical initialization and readout of the spin with an additional coherent control via microwave pulses. The spin defect is highly sensitive to its environment; thus, it is a very interesting platform for nanoscale sensing of strains, temperature, and magnetic fields. In addition to local sensing, the system is a potential candidate for space applications due to its small size and the simple and robust readout configuration. The talk will conclude by discussing the potential of hBN as a future quantum vector magnetometer on spacecrafts to study the interiors of planetary bodies.

BIO: Dr. Andreas Gottscholl is a postdoctoral researcher at the NASA Jet Propulsion Laboratory (JPL) since fall 2022. He joined JPL as a physicist with the focus on applied quantum mechanics, especially quantum sensing and quantum computing. Andreas graduated from the Julius-Maximilian University Wuerzburg, Germany, where he studied spin-defects in solid state systems for various quantum applications. During his bachelor and master he investigated the silicon vacancy in silicon carbide to realize a maser at room temperature. Afterwards in his PhD, he focused on hexagonal boron nitride in which he found and identified the boron vacancy – the very first optical accessible spin defect in this graphene-like 2D material. Besides the identification, he realized a coherent control of this defect at room temperature which is the basis for future quantum computing application. As a further application, he demonstrated the sensor capabilities of this defect (magnetic field, temperature and pressure sensing) based on optically detected magnetic resonance. Within the OPuS-MAGNM project of JPL he continues with the sensor application of spin-defect hosting quantum materials and is currently developing a next-generation optically pumped solid state magnetometer.

Straintronics in 2D Materials

Arend van der Zande
Materials Science and Engineering, Mechanical Science and Engineering
University of Illinois at Urbana-Champaign

Abstract

Recently, strain has emerged as a means to control material and device properties on an unprecedented scale. Two-dimensional (2D) materials are ideal "ultra-strength" systems for tuning properties via strain: they host rich strain-induced quantum behavior, while the lower dimensionality enables new kinds of symmetry changing deformations. However, in many next generation technologies including heterogeneous integration of 2D materials with CMOS processes, wearable electronics, and quantum systems, strain is an important yet unknown or uncontrolled parameter. In this talk, we examine the nanoscale interfacial mechanics for strain engineering in 2D materials, and their influence on the electronic properties and device transport. For example, we demonstrate designable strain using thin film stressors to spatially pattern the electronic structure of 2D monolayers and heterostructures. We then leverage these fundamental insights to apply strain and deformation engineering across a broad range of applications such as mobility enhancement in 2D transistors and stretchable electronics.

BIO: Dr. Arend M. van der Zande is an Associate Professor in Materials Science and Engineering, with affiliations in MechSE, and ECE. His research expertise is on engineering and exploring the unique properties of novel nanosystems from nanomaterial building blocks. He is a team lead on the Illinois Material Research Science and Engineering Center, and is an Associate Editor for the journal ACS Nano Letters. He was awarded the 2022 Society of Engineering Science Young Investigator Medal and the NSF CAREER award, and was on the Clarivate Analytics list of the world's most influential researchers in 2018-2022. He earned a Ph.D. in Physics from Cornell University in 2011 and a B.S in Physics and Mathematics from University of California, Santa Cruz in 2003. He then became a postdoctoral fellow in the Mechanical Engineering and the Energy Frontier Research Center at Columbia University. He has published 80+ articles with >28,000 citations in journals including Nature, Science, Nature Materials, Advanced Materials, and Nano Letters.

Novel 2D Transport Characterizations: All-Electrical Determination of Anisotropic Crystal Orientation and Conductivity Scaling for Tunable Impurity Densities

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Abstract

The crystal orientation of an exfoliated black phosphorous flake is determined via purely electrical means [1]. A sequence of three resistance measurements on an arbitrarily shaped flake with five contacts determines the three independent components of the anisotropic in-plane resistivity tensor, thereby revealing the crystal axes. The resistivity anisotropy ratio decreases linearly with increasing temperature T and carrier density reaching a maximum ratio of 3.0 at low temperatures and densities, while mobility indicates impurity scattering at low T and acoustic phonon scattering at high T.

In addition, a scaling law is demonstrated in the conductivity of gated two-dimensional (2D) materials with tunable concentrations of ionized impurity scatterers [2]. Experimental data is shown to collapse onto a single 2D conductivity scaling (2DCS) curve when the mobility is scaled by r, the relative impurity-induced scattering, and the gate voltage is shifted by V_s, a consequence of impurity-induced doping. This 2DCS analysis is demonstrated first in an encapsulated 2D black phosphorus multilayer at $T = 100$ K with charge trap densities programmed by a gate bias upon cooldown, and next in a Bi_2Se_3 2D monolayer at room temperature exposed to varying concentrations of gas adsorbates. This 2DCS analysis is expected to be applicable in arbitrary 2D materials systems with tunable impurity density, which will advance 2D materials characterization and improve performance of 2D sensors and transistors.

References:

[1] L. Peng, S. A. Wells, C. R. Ryder, M. C. Hersam, and M. Grayson, "All-electrical determination of crystal orientation in anisotropic two-dimensional materials," PRL **120**, 086801 (2018).
[2] C. Wang, L. Peng, S. A. Wells, J. D. Cain, Y.-K. Huang, L. A. Rhoads, V. P. Dravid, M. C. Hersam, & M. A. Grayson. "Field-effect conductivity scaling for two-dimensional materials with tunable impurity density." 2D Materials **9**, 031002 (2022).

BIO: Dr. Matthew Grayson is an expert in the design, fabrication, and electrical and thermoelectric characterization of electronic devices and materials. His initial work in low-dimensional electron systems such as quantum wells, one-dimensional wires, electron-beam patterned structures, and both integer and fractional quantum Hall edges, has led to more recent work on characterizing amorphous and anisotropic materials. In particular, he has developed new advances in thermoelectric materials with the concept of transverse thermoelectrics for integrated thermal management. He has also advanced the understanding of dynamics in amorphous systems that undergo anomalous diffusion. New methods in resistive tomographic imaging are being explored for 3D bioimaging as well as 2D artificial skin sensor applications. Laboratory measurement capabilities include electron transport over a continuous temperature range from 15 mK to 400 K, and high magnetic fields up to 17 T. Systems of interest are thermoelectrics, anisotropic conductors, Luttinger liquids, quantum Hall ferromagnets, Type II superlattices, and multivalley quantum systems. He joined Northwestern in 2007 and has been an associate professor since 2012, and full professor since 2018 in the Department of Electrical and Computer Engineering of Northwestern University.

Development of Next-Generation Quantum Devices and Systems at Argonne CNM

Xu Han
Center for Nanoscale Materials, Argonne National Laboratory

Abstract

Quantum information science harnesses quantum effects to fundamentally advance technologies in major fields of computing, sensing, and communications. The Center for Nanoscale Materials (CNM) at Argonne has dedicated efforts to develop next-generation quantum devices and systems, including superconducting qubits, single-electron-on-solid neon qubits, quantum acoustic devices, microwave-optical quantum transducers, quantum networks, etc. In this talk, I will present a few on-going projects in CNM quantum labs. I will introduce "InterQnet" – a heterogeneous quantum network that we are developing at Argonne. I will then discuss microwave-optical quantum transducers as a key component to realize quantum networks. Finally, I will present our recent demonstration of a fundamentally new type of qubit based on single electrons trapped on solid neon, offering a novel matter qubit platform for quantum processors in the network.

BIO: Dr. Xu Han received his B.S. in physics from Peking University in 2011, and his Ph.D. in electrical engineering from Yale University in 2018. He joined Argonne National Laboratory in 2019 as an Assistant Scientist at the Center for Nanoscale Materials (CNM). He currently serves as the lead of Quantum Matter and Devices Lab, Quantum Optomechanics Lab, and ADR & MEMS Lab at Argonne CNM. He is also a board member of Argonne Quantum Institute. His research focuses on the development of hybrid quantum devices and systems. Topics include microwave-optical quantum transduction, quantum networks, nanomechanical and nanophotonic devices, single-electron qubits, and superconducting quantum systems.

Q-NEXT National Quantum Information Science Research Center

Martin Holt
Center for Nanoscale Materials, Argonne National Laboratory

Abstract

Led by Argonne National Laboratory, Q-NEXT is one of five National QIS Research Centers recently established by the Department of Energy Office of Science to advance quantum science and technology through national laboratories working in partnership with academia and private industry to drive innovative research. Q-NEXT is focused on how to reliably control, store and transmit quantum information through a synthesis of research driving the advancement of quantum materials, computational and networking testbeds, the establishment of two national foundries and the advanced simulation of systems and algorithms for quantum information processing. Recent progress and outlook including work on deterministic control of 2D materials for quantum information science will be discussed in the context of recent results.

BIO: Dr. Martin Holt leads the Extreme Scale Characterization Thrust of Q-NEXT and is the Electron and X-ray Microscopy Group leader of the Center for Nanoscale Materials at Argonne National Laboratory.

Two-Dimensional Neuromorphic Electronic Materials and Applications

Mark C. Hersam
Department of Materials Science and Engineering, Northwestern University

Abstract

The exponentially improving performance of digital computers has recently slowed due to the speed and power consumption issues resulting from the von Neumann bottleneck. In contrast, neuromorphic computing aims to circumvent these limitations by spatially co-locating logic and memory in a manner analogous to biological neuronal networks. Beyond reducing power consumption, neuromorphic devices provide efficient architectures for image recognition, machine learning, and artificial intelligence. This talk will explore how two-dimensional nanoelectronic materials enable gate-tunable neuromorphic devices. For example, by utilizing self-aligned, atomically thin heterojunctions, dual-gated Gaussian transistors have been realized, which show tunable anti-ambipolarity for artificial neurons, competitive learning, spiking circuits, and mixed-kernel support vector machines. In addition, field-driven defect motion in polycrystalline monolayer MoS_2 enables gate-tunable memristive phenomena that serve as the basis of hybrid memristor/transistor devices (i.e., 'memtransistors') that concurrently provide logic and data storage functions. The planar geometry of memtransistors further allows multiple contacts and dual gating that mimic the behavior of biological systems such as heterosynaptic responses. Moreover, control over polycrystalline grain structure enhances the tunability of potentiation and depression, which enables unsupervised continuous learning in spiking neural networks. Finally, the moiré potential in asymmetric twisted bilayer graphene/hexagonal boron nitride heterostructures gives rise to robust electronic ratchet states. The resulting hysteretic, non-volatile injection of charge carriers enables room-temperature operation of moiré synaptic transistors with diverse bio-realistic neuromorphic functionalities and efficient compute-in-memory designs for low-power artificial intelligence and machine learning hardware.

BIO: Dr. Mark C. Hersam is the Walter P. Murphy Professor of Materials Science and Engineering, Director of the Materials Research Center, and Chair of the Materials Science and Engineering Department at Northwestern University. He also holds faculty appointments in the Departments of Chemistry, Applied Physics, Medicine, and Electrical Engineering. He earned a B.S. in Electrical Engineering from the University of Illinois at Urbana-Champaign (UIUC) in 1996, M.Phil. in Physics from the University of Cambridge (UK) in 1997, and Ph.D. in Electrical Engineering from UIUC in 2000. His research interests include nanoelectronic materials, additive manufacturing, scanning probe microscopy, renewable energy, neuromorphic computing, and quantum information science. Dr. Hersam has received several honors including the TMS Robert Lansing Hardy Award, MRS Mid-Career Researcher Award, AVS Medard Welch Award, and MacArthur Fellowship. An elected member of the American Academy of Arts and Sciences, National Academy of Engineering, and National Academy of Inventors, Dr. Hersam has founded two companies, NanoIntegris and Volexion, which are suppliers of nanoelectronic and battery materials, respectively. Dr. Hersam is a Fellow of MRS, ACS, ECS, AVS, APS, AAAS, SPIE, and IEEE, and also serves as an Executive Editor of *ACS Nano*.

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Opportunities in Developing Efficient Electronics via Heterogeneous Integration of 2D and Semiconducting Materials with Diamond

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Abstract

Diamond holds immense promise as a material for high-voltage and extreme-condition power electronics, owing to its exceptional properties such as high thermal conductivity, large electric field strength along with high carrier mobilities and saturation velocities. However, the lack of a reliable method for n-type doping at room temperature has stalled progress in diamond-based electronics. This challenge arises because donor energy levels lie deep within the bandgap, making higher temperatures necessary for sufficient thermal activation of carriers. I'll discuss an alternative pathway that we have developed to overcome this bottleneck by incorporating atomically thin n-type molybdenum disulfide (MoS_2) monolayers as a pseudo delta-doped layer within boron-doped p-type polycrystalline and single-crystal diamond. This enables the creation of vertical 2D/3D heterostructure p-n junction diodes that operate efficiently at room temperature. I will also discuss our previous work with graphene-on-diamond, which demonstrated a record-high current density (~10^9 A/cm^2), achieved through the exceptional thermal interface with diamond, as well as effective thermal management via the direct deposition of nanocrystalline diamond on GaN using a low-temperature CVD process. Our demonstration offers new insights and provides a holistic platform for developing reliable, high-performance diamond-based electronics, integrated with low-dimensional and semiconducting materials for greater efficiency.

BIO: Dr. Anirudha Sumant is a Group Leader of the Nanofabrication and Devices Group and a Materials Scientist at the Center for Nanoscale Materials, Argonne National Laboratory. He leads research on nanocarbon materials, including CVD-diamond, carbon nanotubes, graphene, and other 2D materials. His work focuses on exploring the electronic, mechanical, and tribological properties of carbon-based and 2D materials, alongside heterointegration of materials and advancements in micro-nanofabrication. Dr. Sumant has authored over 170 peer-reviewed publications, two book chapters, and holds 39 patents. His achievements have been recognized with numerous prestigious awards, including four R&D 100 Awards, a NASA Tech Brief Magazine Award, three TechConnect National Innovation Awards, the Pinnacle of Education Award, and the Excellence in Commercialization Award. He is an active member of MRS, STLE, and AVS, and currently serves on the editorial advisory board for Applied Physics Letters as well as a specialty Chief Editor for the journal Frontiers in Carbon.

Atomistic-level understanding and control of defect states in 2D layered materials

An-Ping Li
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Abstract

Electronic devices that leverage single atomic-scale defects represent the leading edge of device miniaturization, offering ultra-low energy consumption and great potential for microelectronics and quantum technologies. Progress in this field hinges on precise, atomistic-level control and understanding of defect states. In two-dimensional (2D) materials, each atom and defect site is accessible to both optical and electronic characterization. Scanning tunneling microscopy (STM), with its powerful imaging, spectroscopy, and manipulation capabilities at the atomic scale, enables detailed identification, manipulation, and even custom creation of specific defect structures. This presentation explores the dual role of STM as a characterization and control tool to enable deterministic understanding and manipulation of defect states. By developing specialized single- and multi-probe STM techniques, informed by theoretical insights and artificial intelligence, we can efficiently identify intrinsic defects and evaluate their potential for device applications. These techniques enable the controlled creation and modification of defect sites, facilitating the assembly of intentionally designed structures and underscoring STM's critical role in advancing both microelectronics and quantum information sciences.

This research was conducted at the Center for Nanophase Materials Sciences, which is a DOE Office of Science User Facility.

BIO: Dr. An-Ping Li is the Leader for Scanning Tunneling Microscopy Group, and the Leader for Heterogeneities in Quantum Materials Theme in Center for Nanophase Materials Sciences (CNMS) division at the US Department of Energy's (DOE) Oak Ridge National Laboratory. He received his Ph.D. degree in Condensed Matter Physics in Peking University in 1997 where his dissertation research emphasized the optoelectronic properties of nanomaterials. He then went to Max-Plank-Institute in Halle, Germany as a MPI Fellow to work on self-assembly of ordered nanostructures. In 1999, he joined the Center for Sensor Materials in Michigan State University as a visiting scholar to develop thin film growth of crystalline diamonds. After a brief stint in a start-up company, Galian Photonics in Vancouver, Canada trying to commercialize photonic crystal technologies, he came back to USA and joined the Oak Ridge National Lab in 2002. He moved through the ranks from Research Associate, Research Staff, Senior Research Staff, to Distinguished Staff. In the meantime, he holds joint appointments with the Department of Physics and Astronomy of the University of Tennessee in Knoxville, first as an Adjunct Associate Professor and then a Joint Faculty Professor.

Optically-active van der Waals solids realized through bottom-up and top-down synthesis routes for sensors and quantum-enabled devices

Anupama B. Kaul
PACCAR Professor of Engineering; Materials Science and Engineering and Electrical Engineering, University of North Texas

Abstract

Light-matter interactions in semiconducting two-dimensional (2D) crystallites, their strain-dependent emission properties and pristine atomically flat interfaces, coupled with the ability to solution-process these materials, offer exciting prospects for both fundamental scientific discovery and technologically-relevant innovations to arise from these fascinating materials. In this talk, we will discuss our recent work on the light-matter interactions in superconducting $NbSe_2$ and semiconducting WSe_2 toward sensing devices enabled by quantum phenomena. In the latter case, vapor-grown crystalline WSe_2 exhibit localized excitons, where defect engineering can be used to influence the emission characteristics, which is considered as one of viable means for the observation of quantum emitters in these systems. When such crystallites are free from the substrate, the electron-phonon interactions can be deciphered through temperature-dependent photoluminescence (PL) spectroscopy. An enhancement in intensity of the localized excitons in suspended WSe_2 is observed. We also present our findings from local nanoscale strain engineering, where a uniaxial force induced on the suspended membranes with atomic force microscopy results in the modulation of the strain-dependent emission characteristics. Finally, solution-processed 2D materials, including lower dimensionality perovskites, have provided a pathway to realize a rich plethora of flexible and bendable optoelectronic sensing devices on flexible and compliant substrates using low-cost, additive manufacturing techniques, which will also be discussed.

BIO: Dr. Anupama B. Kaul is the PACCAR Professor of Engineering at the University of North Texas (UNT). She serves as PI and Center Director of the SEEP-IT Consortium, awarded to UNT from the Department of Energy in 2023. Prior to UNT, Dr. Kaul was Associate Dean for Research and Graduate Studies and held the AT&T Distinguished Professorship in ECE at the University of Texas, El Paso. Dr. Kaul has served as a Program Director at the National Science Foundation (NSF), where she was on rotation as an IPA from the Jet Propulsion Laboratory (JPL)-NASA, California Institute of Technology (Caltech). She is the recipient of the NSF Director's Award for Program Management Excellence. During her 12-year tenure at JPL-NASA, Caltech, she received the NASA Service Award, a NASA Team Technical Accomplishment Award, multiple NASA Patent Awards and numerous NASA Tech. Brief Awards for her research. In 2012, she was selected to be a participant at the US NAE Frontiers of Engineering (FOE) Symposium, and the bi-lateral Indo-US FOE, also organized by the US NAE. Dr. Kaul is Fellow of SPIE, Fellow of the Class of 2016 ELATE's executive leadership development program. She obtained her graduate degrees from the UC Berkeley.

From Pixels to Properties: Integrating multimodal STEM and Machine Learning for Advanced Characterization of 2D Materials

Roberto dos Reis[1,2,3], Gabriel T. dos Santos[1], Yukun Liu[1], Patricia E. Meza[1], Alfred Yan[1], Vinayak P. Dravid[1,2,3]

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Abstract

Recent advances in electron microscopy instrumentation, particularly novel electron detectors and high-throughput data acquisition systems, have opened new frontiers in the characterization of two-dimensional (2D) layered materials. Our integrated approach combines multimodal scanning transmission electron microscopy (STEM) techniques - including 4D-STEM for local strain mapping at atomic resolution, simultaneous HAADF/ABF imaging, and spatially-resolved EELS capturing electronic structure variations - with advanced data science techniques to probe the atomic and electronic structure of novel 2D metal chalcophosphates. We demonstrate how the synthesis and characterization of layered selenophosphates and thiophosphates benefit from this multimodal methodology.

The designed workflow leverages high-speed electron detectors and automated acquisition protocols to collect and process terabyte-scale, hyperspectral datasets across multiple STEM modalities. Through the implementation of physics-informed neural networks specifically designed for 4D-STEM data, we enable automated identification of strain fields and electronic structure variations, alongside traditional dimensionality reduction techniques and deep learning frameworks to extract previously inaccessible information about local atomic configurations and chemical bonding in these materials. This approach enables unprecedented insights into the structure-property relationships that govern their magnetic and ferroelectric properties, particularly in the few- and single-layer regime. We will discuss specific case studies demonstrating how this characterization framework accelerates materials discovery and optimization while providing fundamental understanding of emergent phenomena in 2D layered systems.

BIO: Dr. Roberto dos Reis is a Research Assistant Professor and Lecturer at Northwestern University, specializing in the convergence of advanced electron microscopy and data science for materials characterization. At Northwestern's NUANCE center, he pioneers quantitative electron microscopy techniques, including 4D-STEM and in-situ S/TEM, while developing innovative AI-driven approaches for materials analysis. His research implements cutting-edge characterization methods for complex materials systems, integrating advanced microscopy with emerging artificial intelligence strategies. Dr. dos Reis holds a Ph.D. in Physics and leads initiatives in microscopy automation and intelligent data analysis, advancing the field through novel computational approaches.

A Logic Roadmap for the FAB Compatible Integration Of Low Dimensional Materials: Strategy, Challenges And Opportunities

César Javier Lockhart de la Rosa
IMEC

Abstract

Silicon has reigned unchallenged in the semiconductor industry for the past generations. This is especially true for logic applications. But will this also be the case for the generations to follow? The uprise of low dimension semiconducting materials such as 2D transition metal dichalcogenides (TMDCs) or 1D carbon nano tubes (CNTs) pose, at the very least, a considerable challenge. While their potential and fundamental limits have been shown in literature, major hurdles remain to be tackled before even considering viable applications that benefit from these materials. This is especially true when industrially relevant methods and compatibility is also considered instead of the academic freedom frequently exercise in the performance demonstrations up to date. Can we growth/deposit/transfer these materials in industrially relevant sizes using FAB compatible tools? Can we properly contact these materials with Fab compatible processes? What applications will benefit the most? What is the strategy for the introduction of this materials, and at what technology nodes can we expect to do so? I will address some of the answers to these questions based on a decade of research by IMEC's Exploratory Logic program.

BIO: Dr. César Javier Lockhart De La Rosa received his B.S. degree in electronic engineering from Universidad APEC, Dominican Republic, and the M.Sc. degree in nanoscience and nanotechnology from KU Leuven, Belgium, and Chalmers University, Sweden, in 2012. After that he got his Ph.D. degree from KU Leuven in collaboration with imec, Belgium, in 2017 and post-Doc in 2018 tackling the contacts and doping of 2D TMDCs and graphene-based transistors for logic applications. He then worked as a researcher at imec in different domains such as selector devices for memory applications and DNA for data storage before becoming the program manager for Exploratory Logic program where he drives the efforts to identify and integrate the next generation logic devices.

Working with Argonne, a Partner in Innovation

Phillip Smith
Argonne National Laboratory

Abstract

Argonne researchers tackle the critical scientific challenges of our time – from the design of novel energy materials and nanomaterials to their development and scale-up for manufacturing, to advanced measurement and computational science. Our research is enabled by our people and our world-class facilities and scientific instruments. At Argonne, an important part of our mission is focused on how partnerships can help translate these unique resources and our scientific discoveries into tomorrow's innovations. This introductory overview will cover our partnership objectives at the lab, and the process and mechanisms available to partner with Argonne.

BIO: Dr. Phil Smith is a Strategic Programs Manger within Argonne's Science and Technology Partnerships and Outreach directorate. Phil supports Argonne's efforts to advance external partnerships and commercialization of materials technologies. Phil also has a leadership role in Q-NEXT, the Argonne-led DOE Office of Science National Quantum Information Science Research Center, where he has responsibilities in management of center ecosystem efforts, partnerships, and supporting center operations. Phil holds a Ph.D. in Materials Physics from The Ohio State University, and an M.S. in Business Analytics from The Georgia Institute of Technology.

A Group Theory-Based Approach to the Design and amplification of synthetic nonlinearities

Andrew Tyler Aoueille[1,2], Araceli Herrera Mondragon[1,2], Noah Benjamin Hurley[1,2], Noel Martinez[1,3], Yuankun Lin[2], Anupama Kaul[3] and Ihab El-Kady[1,2]

[1] Dept. of Photonic and Phononic Micro Systems, Sandia National Laboratories; [2] Dept. of Physics, University of North Texas; [3] Dept. of Materials Science & Engineering, University of North Texas

Abstract

Optical nonlinearities play a pivotal role in many quantum computing applications an area of prime importance to governmental initiatives and an exponentially emerging technological theme in the industry. Applications range from quantum network interconnects, the creation of deterministic two-qubit optical gates, the creation of squeezed light states, and quantum sensing. Of interest is Quantum networking and distributed quantum sensing which require photonic links (flying qubits) to connect nodes and enable scaling to larger distances and network sizes. Particularly, in heterogenous networks where different nodes performing different functions generally operate at different wavelengths, quantum information preserving frequency conversion is required.

In my talk I will focus on the creation and amplification of synthetic nonlinearities via group theory-based symmetries engineered to guarantee automatic phase matching and selective amplification of desired nonlinear conversion channels at the expense of undesired alternate decay routes. Not only that, but this group theory approach provides us with a unique vehicle to observe new unconventional nonlinear phenomena never observed before. Furthermore, I will cover ongoing collaborative efforts aiming to hybridize photonic and metamaterial structures with extraordinary nonlinearities housed in 2D materials, aiming to create robust optical cavity designs for efficient parametric nonlinear conversion. Fabrication and experimental plans will be outlined. Latest modelling and simulation results showing the anticipated favourable performance and design robustness will be discussed.

BIO: Dr. Ihab El-Kady is a Distinguished Member of Technical Staff at Sandia National Laboratories. He obtained his Ph.D. in Condensed Matter Physics from Iowa State University in 2002. He has 170+ publications and 20+ patents. His expertise and interests lay in applications of wave propagation in complex media and spans the areas of EM modelling and simulation, EM and Mechanical Metamaterials, Plasmonics, Photonic and Phononic Crystals, Thermal emission and Piezoelectrics for communication, sensing and power transduction. He was the lead PI of multi-award-winning MIRaGE Meta-material design/simulation tool.

Scalable Models for Microelectronics Workforce Development

Kerrie Douglas, Tamara Moore, Melissa Dyehouse, Alejandro Strachan, Peter Bermel
Purdue University

Abstract

The CHIPS and Science Act passed in 2022 has incentivized leading manufacturers to reshore their capabilities, including Intel, Micron, TSMC, and many more. To meet ambitious targets for increased design and production capabilities, a larger and highly capable U.S. citizen workforce is necessary. In fact, most CEOs have identified this as the greatest risk factor to further growth. If nothing further is done, the U.S. faces a shortage of over 60,000 semiconductor engineers, technicians, and computer scientists with a bachelor's degree or higher by 2030 to work at public and private employers. The **SCALE program** was created to build up the U.S. talent pipeline in specialized fields, from K-12 through continuing education. Since its launch, SCALE has grown from an initial cohort of 25 students in Summer 2020 to 1,000 students life-to-date, of whom 75% have pursued employment or graduate studies in the defense microelectronics sector. In this talk, I'll summarize recent developments in the broader landscape of microelectronics workforce development, talk about the approach and capabilities of our program, and provide recommendations for future efforts, including potential metrics of success.

BIO: Dr. Peter Bermel is the SCALE Principal Investigator and Co-Director. SCALE is the preeminent national program for developing the U.S. defense microelectronics workforce, with 1,000 students joining since February 2020. As a Professor of Electrical & Computer Engineering, he also leads the Energy & Nanophotonics research group at Purdue University, which leverages nanophotonics to improve the performance of microelectronics and energy systems. He has also served as the PI for the ASSURE center for secure microelectronics, and received over 40 awards from major research sponsors, such as the Department of Energy, the Semiconductor Research Corporation, Northrop Grumman Corporation, NEC Corporation, the Purdue Research Foundation, Applied Research Institute, and the Department of Defense. He is a recipient of a National Science Foundation (NSF) CAREER award, a Winston Churchill Foundation Scholarship, an NSF Graduate Research Fellowship, an MIT Compton Fellowship, and the Elmore Named Professor Position. Dr. Bermel is widely published in scientific peer-reviewed journals, and has been cited over 10,500 times, for an h-index of 42. His work is a recurring topic in publications geared towards the general public, including the Washington Post, NPR, IEEE Spectrum, and ComputerWorld – most recently, for his work on microelectronics workforce development.

Nanotechnology-Enabled: The Quantum and Micro/Nano electronics Workforce

Quinn Spadola
Deputy Director, National Nanotechnology Coordination Office

Abstract

Workforce development can be a limiting factor of growth for emerging industries if needs are not anticipated and prepared for. This talk will focus on how federal investments in the nanotechnology field can be leveraged by the quantum and the micro/nano electronics industries to accelerate workforce development and growth.

For more than 20 years, the National Nanotechnology Initiative (NNI) has supported the development, design, and curation of educational materials to expand the awareness and interest of nanotechnology as a career path and enhanced the skilled domestic workforce in the field. Nanotechnology principles and phenomena enable the quantum and micro/nano electronics industries. These industries can leverage the wealth of expertise, programs, and materials already developed by the NNI community to accelerate the development of their workforce.

The existing NNI resources can be used to spark students' interest in the science of the very small. For example, the nanotechnology community has developed free educational resources for teachers available at NNCI.net, nanoHUB, and micronanoeducation.org. The NNI also supports the Remotely Accessible Instruments for Nanotechnology (RAIN) Network which offers remote access to nanotechnology instrumentation to classrooms across the country. With this resource students can visually explore the nanoscale and see what happens when quantum effects take over. Past federal investments in nanotechnology have supported networks of centers, research facilities, and instrumentation that are now the basis of new centers focused on the development of quantum and micro/nano electronics. The future of the quantum and micro/nanoelectronics fields relies on the work of the NNI.

BIO: Dr. Quinn Spadola is the Deputy Director of the National Nanotechnology Coordination Office (NNCO). She has been a member of the National Nanotechnology Initiative community since her graduate studies. Prior to returning to the NNCO, Dr. Spadola was Associate Director of Education for the National Nanotechnology Coordinated Infrastructure (NNCI), a network of open nanotechnology laboratory user facilities supported by the National Science Foundation, and the Director of Education and Outreach for the Southeastern Nanotechnology Infrastructure Corridor NNCI site at the Georgia Institute of Technology. Dr. Spadola began her time at the NNCO as a AAAS Science and Technology Policy Fellow in 2014. After her fellowship, she served as Education and Outreach Coordinator and Technical Advisor to the Director until 2018. She received her Ph.D. in physics from Arizona State University and her MFA in Science and Natural History Filmmaking from Montana State University.

Overview of Argonne University Programs and Partnerships

Robert Schuch
Argonne National Laboratory

Abstract

Argonne National Laboratory hosts nearly 1,200 undergraduate and graduate students in research internship experiences each fiscal year. Collegiate students' work with their research mentors to support the laboratory's current multidisciplinary science and engineering research portfolio that seeks to address the biggest questions facing humanity.

The University Programs and Partnerships Team leads the efforts on behalf of the laboratory to support these research experience for students and research mentors throughout all points of the process – from recruitment, to participating in the program, and after the appointment to support student success in the future. A new focus on university partnerships has included internal stakeholder engagement and external university faculty engagement to support research collaborations to drive forward Argonne's current strategic research initiatives.

This presentation will provide an overview of the available undergraduate and graduate research internship experiences offered at Argonne. Additionally, faculty exchange programs and grant collaboration opportunities will be highlighted.

BIO: Dr. Rob Schuch is a University Partnership Program Manager who comprehensively facilitates the development and implementation of the undergraduate programs at Argonne. Throughout the year, he plans out the spring, summer, and fall undergrad internship programs, organizing both the specifics for the programs and how to best recruit participants and volunteers. For the internships, he creates a diverse set of activities including Lunch with a Researcher events, professional development seminars, and more. Rob also regularly manages and updates Education's public website. His goal is to ensure that students can make the most of their time at Argonne through immersive programming and networking opportunities.

Invited Panelist Biographies

Ann Cavallo, Ph.D.
Panelist A
The University of Texas at Arlington

Dr. Ann M.L. Cavallo, Ph.D., is Assistant Vice Provost and Director of the Center for Research on Teaching and Learning Excellence (CRTLE), Co-director of UTeach Arlington, and Distinguished University Professor of Science Education at the University of Texas at Arlington (UTA). She earned her B.S. from Niagara University, and two master of science degrees and a Ph.D. in science education from Syracuse University. She taught middle and high school biology, chemistry, Earth science, and general/physical science prior to earning her graduate degrees. At UTA she has held leadership positions including Associate Dean in the College of Education and founding Co-director of UTeach Arlington. She has designed, directed, and taught in undergraduate and graduate programs both on campus and online including in STEM teaching, educational psychology, research methods, and life/earth science. In her current position she designs and leads professional development programs for faculty and GTAs in all disciplines. Dr. Cavallo's research investigates high school and college students' learning approaches and processes, scientific reasoning, self-efficacy, and their acquisition of conceptual understandings of science, particularly through inquiry-based teaching models. She is Principal Investigator of three active National Science Foundation Noyce grants and overall has secured more than $15 million in grants and gifts to support education. Dr. Cavallo has widely published and presented her work at professional conferences and has held leadership positions in education organizations. In 2015, Dr. Cavallo earned the UTA Distinguished Record of Research Award, and in 2016, was inducted into the Academy of Distinguished Scholars. In 2023, Dr. Cavallo was named a lifetime Fellow of the *American Association for the Advancement of Science* (AAAS) for distinguished contributions to the advancement of science education, particularly for her work with STEM teachers.

Qinglong Jiang, Ph.D.
Panelist B
Department of Chemistry and Physics,
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Dr. Qinglong Jiang is an associate professor in the University of Arkansas at Pine Bluff, managing editor for Engineered Science, FESS fellowship. His research areas are focusing on the design new methods and nano-micro materials for electro-optical devices, sensor, drug delivery, solar cells, light emitting (crystal and film) as well as some other related areas. His research has been supported by NSF, DOE, INBRE and other foundations. His has over 100 publications and over 50 presentations including keynotes and invited talks.

Jermiah K. Billa, Ph.D.
Panelist C
Alcorn State University, Lorman, Mississippi

Dr. Jermiah Billa currently serves as Chairman, Tenured Associate Professor, Program Director of Radiation Health Physics program, and Director of Applied Science & Technology Graduate Program in the Advanced Technologies Department at Alcorn State University, Mississippi. He possesses extensive experience in teaching, research, and administration. His areas of research include applied health physics, radiation monitoring, nuclear instrumentation & radiation detection, dosimetry, and STEM education. Under his leadership, the health physics program has expanded significantly in the areas of student enrollment, student retention, and research. His other experiences include grant writing, advisement of students, curriculum development, capacity building, and initiation of collaborations with various private and federal organizations. In the last four years, he has secured more than $5 M in funding from various private and federal organizations. He is instrumental in development of collaborations with Entergy, Nissan, Los Alamos National Laboratory, Y-12/ Oakridge National Laboratory, University of Utah, Jackson State University, Fisk University, Colorado State University, Southern University New Orleans, NHS College (Native-American College, ND), and Alabama A & M University. Over the last five years, he supervised more than fifty students and most of them graduated and secured permanent positions in the nuclear/radiation industry. Under his leadership the department has extensively progressed in the areas of student enrollment and retention. In July 2014, the national Health Physics Society recognized him with "Excellence in Health Physics Program Development and Student Mentorship" award for his outstanding services to the radiation world. He served as an elected board of directors (2017-19) of the radon/environmental section of the national Health Physics Society (HPS). In 2021, the Mississippi State's Institute of Higher Learning (IHL) recognized him with "Excellence in Diversity and Inclusion" award for his commitment in advancing diversity in STEM fields. In February 2024, the Mississippi Academy of Sciences recognized him at the annual meeting for his significant contributions toward STEM education. In February 2024, the Mississippi Academy of Sciences (MAS) recognized him with "Moderator of STEM Scholars Symposium Award" for his commitment to STEM education & STEM outreach activities. In Summer 2024, Alcorn State University's Upward Bound Program honored him with, Upward Bound Faculty Support Award of the Year for his strong support to the ASU's Upward Bound Program.

Patrick Chu, Ph.D.
Panelist D
Sandia National Laboratory

Dr. Patrick B. Chu received his B.S. degree in EE from MIT, Cambridge and his M.S. and Ph.D. degrees in EE from UCLA. He has conducted research in MEMS, sensors, data storage, and photonics devices at several different research organizations and companies including Jet Propulsion Laboratory, Tanner Research, Tellium, Inc., and Seagate Technology. Since 2011, he has been the manager of the Applied Photonics Microsystem department at Sandia National Laboratories, focusing on photonics technologies for national security applications. He has over a dozen patents and has co-authored several dozen conference, journal, and invited papers.

Quinn Spadola, Ph.D.
Panelist E
Deputy Director, National Nanotechnology Coordination Office

Dr. Quinn Spadola is the Deputy Director of the National Nanotechnology Coordination Office (NNCO). She has been a member of the National Nanotechnology Initiative community since her graduate studies. Prior to returning to the NNCO, Dr. Spadola was Associate Director of Education for the National Nanotechnology Coordinated Infrastructure (NNCI), a network of open nanotechnology laboratory user facilities supported by the National Science Foundation, and the Director of Education and Outreach for the Southeastern Nanotechnology Infrastructure Corridor NNCI site at the Georgia Institute of Technology. Dr. Spadola began her time at the NNCO as a AAAS Science and Technology Policy Fellow in 2014. After her fellowship, she served as Education and Outreach Coordinator and Technical Advisor to the Director until 2018. She received her Ph.D. in physics from Arizona State University and her MFA in Science and Natural History Filmmaking from Montana State University.

Robert Schuch, Ph.D.
Panelist F
Argonne National Laboratory

Dr. Rob Schuch is a University Partnership Program Manager who comprehensively facilitates the development and implementation of the undergraduate programs at Argonne. Throughout the year, he plans out the spring, summer, and fall undergrad internship programs, organizing both the specifics for the programs and how to best recruit participants and volunteers. For the internships, he creates a diverse set of activities including Lunch with a Researcher events, professional development seminars, and more. Rob also regularly manages and updates Education's public website. His goal is to ensure that students can make the most of their time at Argonne through immersive programming and networking opportunities.

Robustness of Triple-Cation Perovskite Photo-Absorbers Under Exposure to Gamma-Ray Radiation

Eli Gabaldon[†], Brendan Jones[†], Rasool Kenarangui[+], Weidong Zhou[+], and Anupama B. Kaul[†,‡]
University of North Texas

Abstract

Halide perovskites have now garnered significant attention for their attractive photoabsorption features, including in detectors and solar cells. Their photoabsorption robustness in high, ambient radiation particularly ionizing gamma radiation (γ-ray), is also highly relevant for certain applications in nuclear-rich environments. In this work, we provide an initial assessment of triple-cation perovskites (TCPs) with the specific formulation comprised of $Cs_{0.05}FA_{0.79}MA_{0.16}PbI_{2.45}Br_{0.55,}$ after exposure to γ-ray radiation. The TCP's characterization includes examining photoluminescence (PL) emission of spin-cast films, while the optoelectronic measurements of the photocurrent (I_{ph}) showed the devices to be relatively robust after exposure to the ambient radiation. This preliminary study is an initial step to continue to examine the intrinsic properties TCPs under exposure to ionizing radiation for next generation detectors, and related device applications.

BIO: Eli Gabaldon is an electrical engineering undergraduate, earning his BSEE in December 2024. Eli's research focus is on the characterization of perovskites under the influence of gamma radiation. He will continue researching at University of North Texas while earning his Master's degree. Eli's interest in the nanoscale and semiconductors started during the nationwide conversation about the chip shortage and the CHIPS act. Previous to starting his EE degree plan Eli worked in construction project management building commercial concrete structures and studied history at Texas Tech University. He is a member of IEEE-HKN Lambda Zeta and was born in west Texas and raised in the Dallas area. Eli's favourite band is The Doors and he loves going to the movies and used bookstores.

Research capability development to study twisted 2D materials properties at University of Arkansas at Pine Bluff

Manoj Shah, Shrawan Roy, Qinglong Jiang, and Mansour Mortazavi
University of Arkansas at Pine Bluff

Abstract

In this Consortium, the highly collaborative theoretical and experimental efforts aim to discover the underlying science principles in semiconductor materials, focusing on novel 2 Dimensional twisted thin films that demonstrate energy-efficient electronics, photonics and integrated technologies. The research at the University of Arkansas at Pine Bluff (UAPB) focuses on the experimental characterization of optical and electronic properties of twisted thin films to understand the connection to material properties. To achieve these goals, UAPB is expanding its research capability in addition to the existing optical characterization facilities for more sensitive and selective determination of twisted thin films.

BIO: Dr. Manoj Shah is a postdoctoral fellow at the University of Arkansas at Pine Bluff with research focus on developing GeSn, III-V on Sapphire, and 2D materials based optoelectronic devices.

Study of Temperature-dependent Raman Modes of 2D Semiconductors and their Heterostructure

Candace Smith, Sangeeta Sah, Shrawan Roy, Manoj Shah, Qinglong Jiang, and Mansour Mortazavi

University of Arkansas at Pine Bluff

Abstract

Transition metal dichalcogenides (TMDs) are layered semiconductor materials held together by weak van der Waals force because of that, they can be exfoliated up to a monolayer. These materials have interesting layer-dependent optoelectronic properties, which make them highly applicable in future flexible optoelectronics. Raman spectroscopy is one of the non-destructive optical characterization techniques for these materials because they have characteristic unique layer-dependent Raman vibrational modes. In this study, the temperature-dependent Raman measurements were performed for exfoliated few layers of molybdenum disulfide (MoS_2), tungsten disulfide (WS_2), and their heterostructure from 90 K to 300 K using 532 nm laser excitation. The Raman modes observed for these materials follow a systematic red-shift upon heating, suggesting softening of Raman modes with increasing temperature, and furthermore will be presented.

BIO: Candace Smith is a graduate student in Computer Science and Technology at the University of Arkansas at Pine Bluff. With an undergraduate degree in Business Management, Candace brings technical skills and strengths in decision-making and business communication. She is driven to grow as both a programmer and a researcher.

Characterization of Photonically-Cured Semiconducting WSe_2 Films on Silicon and Integration into Perovskite Solar Cells

Brendan Jones†, Sujan Aryal†, and Anupama B. Kaul†,‡

†Department of Electrical Engineering, University of North Texas, Denton, TX 76207; ‡ Department of Materials Science and Engineering, University of North Texas, Denton, TX 76207, USA ; Nanoscale Materials and Devices Laboratory (NMDL)

Abstract

Tungsten diselenide (WSe_2) is a transition metal dichalcogenide (TMD) with electrical properties that enable it to act as a direct band gap semiconductor when in its mono-layer form, offering a wide range of applications. By using a photonic curing system (PCS), we can anneal thin-film substrates that contain two-dimensional (2D) materials within milliseconds without harming the substrate using xenon flashlamps in contrast to conventional thermal annealing treatments. WSe_2 and other 2D materials are attractive candidates to act as hole transport layers (HTLs) in the architecture of perovskite solar cells. In this work, we have conducted experiments with chemically exfoliated WSe_2 ink that is spin-coated on a conventional thermally oxidized silicon (SiO_2/Si) substrate, which is then photonically cured and contacted with titanium (Ti) electrodes. Photonic curing tests were then initiated on the spin coated films to determine the most optimal PCS conditions to then be used on a solar cell's HTL. Our initial results of this experiment intend to reveal the effect on the properties of photonically-cured WSe_2, which would allow us to characterize this emerging semiconducting material to be incorporated into future electronic, optoelectronic, and photovoltaic devices

BIO: Brendan Jones is an Electrical Engineering graduate student currently working as a research assistant in the Nanoscale Materials and Devices Laboratory (NMDL) under the direction of Dr. Anupama Kaul at the University of North Texas (UNT). He graduated with his B.S. in Electrical Engineering at UNT in the Fall of 2023. As a senior design project, he designed a system with a team that collects and transmits noise emission data from unmanned aerial vehicles (UAVs) to a ground system to predict its noise impact on the ground using Arduinos, sensors, OLED displays, and transceivers. Since the summer of 2023 in NMDL, he has conducted research into photonic curing incorporated into the fabrication of perovskite solar cells with the intention of improving stability and power conversion efficiency, as well as photonically curing graphene, tungsten disulfide, and tungsten diselenide ink to increase conductivity of these solution-processed films which can also be incorporated onto low-temperature flexible substrates. He anticipates graduating with his Masters, completing his thesis research, at the end of Fall of 2025.

Laser-radiation Hardened 2D and 3D Organic-inorganic Perovskite Crystals

Steve Kamau, Noah Hurley, Anupama B. Kaul and Yuankun Lin
University of North Texas

Abstract

The layer edge states or low energy state (LES) in 2D hybrid organic-inorganic perovskites have demonstrated prolonged carrier lifetime for a better performance of optoelectronic devices. However, the fundamental understanding of LES in 2D perovskites is still not conclusive. Here we present a photoluminescence (PL) study of LES in 2D Ruddlesden-Popper perovskites of n=2 and n=3 from their cleaved cross sections that are more stable than the natural edge. Our PL measurements have clearly observed reversible, and irreversible surface relaxations (case I and case II) in three laser intensity ranges, further supported by a PL excitation cycle from low to high laser intensity, and vice versa. The PL wavelength of LES is tunable with laser intensity and blueshifts with increasing laser intensity during irreversible surface relaxation process (case I). A fluorescence lifetime imaging (FLIM) shows the LES has a longer lifetime than the band-edge (BE) emission in the sample without a photo-degradation while the BE lifetime become relatively longer in the area with a photo-degradation. The presented laser tunable LES and related irreversible relaxation process provide a new insight that can help to improve the photo-stability in 2D perovskites and understand roles of LESs in optoelectronic device performance.

BIO: Steve Kamau is a Ph.D. candidate in physics at the University of North Texas, where they also completed their undergraduate studies. Their academic focus is on photonics and photonic crystals, with an emphasis on experimental work. Throughout their studies, they have gained hands-on experience in fabricating and measuring photonic crystals in the lab. Their doctoral research, titled "Optical Properties of Twisted Single-Layer Photonic Crystals and Halide Perovskite and Their Potential Integration," explores the incorporation of halide perovskites into photonic crystal resonance cavities, aiming to enhance the performance of these materials for future optical applications.

In addition to their academic work, Steve is currently completing a year-round internship at Sandia National Laboratories, where they continue to gain valuable experience in a research environment. While their post-graduation plans are still undecided, they remain open to exploring diverse career opportunities in both academia and industry. Outside of their academic pursuits, Steve is an avid soccer fan, with a strong passion for Liverpool FC. Their hobbies include playing soccer and listening to music.

Morphological Study on the Nucleation Properties of Quasi-2D Perovskite Thin Films for Renewable Energy Harnessing

Thomas Mather† and Anupama B. Kaul†‡
†Department of Electrical Engineering, University of North Texas, Denton, TX 76207, U.S.A.
‡Department of Materials Science and Engineering, PACCAR Technology Institute, University of North Texas, Denton, TX 76207, U.S.A.

Abstract

Three-dimensional perovskites (3DP) have rocketed to the front of modern thin-film solar cell technology due to their remarkable optoelectronic properties. Despite these properties, 3DP solar cells are often inadequate and degrade when subjected to environmental conditions such as changes in temperature, moisture levels, or even sunlight itself. Ruddlesden-Popper phase two-dimensional perovskite (2DP) films are the lower-dimensional counterpart to 3D perovskites and have shown increased stability when compared to 3DP. However, 2DP-based devices tend to suffer from problems attributed to inherent poor charge transport characteristics caused by organic spacer cations between the conductive inorganic layers. To improve charge transport, we can improve the morphology of the 2DP, ideally making the film near single-crystalline quality. Near single crystal perovskites have a strongly preferential out-of-plane alignment with respect to contacts in planar devices facilitating improved charge transport. In this article, we report on how changes in film annealing temperature, specifically during fabrication, can affect the crystallography of 2DP. To examine film surface morphology after synthesis, SEM and AFM images were taken of each fabricated device showing uniform films as well as roughness differentiations induced by variable annealing conditions. Photoluminescent spectroscopy (PL) was performed for each annealing temperature monitoring shifts in the spectra with corresponding shifts in temperature. The DC transport via Current-Voltage probing was used to monitor the charge transport characteristics of each respective film. Lastly, solar cells were fabricated with the aforementioned 2DP absorber layers hot casted at various temperatures.

BIO: Thomas Mather is a third year PhD candidate in electrical engineering at the University of North Texas (UNT) and recently passed his Phase III qualifying exam at UNT in Spring 2024, with an anticipated PhD graduation date of Spring'26. His research focuses on perovskite-based solar cells and 2D material-based gas sensors with an overarching focus on environmental sustainability embodying both of these domains. Thomas is a Research Assistant in the Nanoscale Materials and Devices Laboratory working under the direct supervision of Dr. Anupama Kaul. He has made advances in perovskite-based solar cell performance using interfacial engineering, as well as developing a recipe for graphene-based environmental gas sensors using prominent chemical exfoliation techniques paired with device level design, such as PCB development and power electronic engineering. Thomas has two publications that are currently in submission and undergoing review. He is actively involved in presenting his research findings to the broad scientific community, having authorships and/or co-authorships in over 15 conference proceedings articles, and has given both poster and oral presentations at international conferences hosted by SPIE, TMS, MRS, and TechConnect. Thomas has also received awards for poster presentations, specifically at the IEEE fall 2022 and 2023 Metrocon conferences, and has served as the Lead Teaching Assistant for coordinating laboratory modules of the Micro Electromechanical Systems (MEMS) Course in the EE Department at UNT over the past three years. Thomas has extensive expertise in semiconductor process engineering, thin films, along with hands-on experience in a suite of characterization techniques and measurement instrumentation.

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Study of Temperature-dependent Raman Modes of 2D Semiconductors and their Heterostructure

Candace Smith, Sangeeta Sah, Shrawan Roy, Manoj Shah, Qinglong Jiang, Mansour Mortazavi
University of Arkansas at Pine Bluff

Abstract

Transition metal dichalcogenides (TMDs) are layered semiconductor materials held together by weak van der Waals force because of that, they can be exfoliated up to a monolayer. These materials have interesting layer-dependent optoelectronic properties, which make them highly applicable in future flexible optoelectronics. Raman spectroscopy is one of the non-destructive optical characterization techniques for these materials because they have characteristic unique layer-dependent Raman vibrational modes. In this study, the temperature-dependent Raman measurements were performed for exfoliated few layers of molybdenum disulfide (MoS_2), tungsten disulfide (WS_2), and their heterostructure from 90 K to 300 K using 532 nm laser excitation. The Raman modes observed for these materials follow a systematic red-shift upon heating, suggesting softening of Raman modes with increasing temperature, and furthermore will be presented.

BIO: Candace Smith is a graduate student in Computer Science and Technology at the University of Arkansas at Pine Bluff. With an undergraduate degree in Business Management, Candace brings technical skills and strengths in decision-making and business communication. She is driven to grow as both a programmer and a researcher.

Monolayer Vapor-grown WSe_2 for Optoelectronic Devices Formed using Scalable, Low-cost Material Integration Schemes

Utsab Kafley[†], Anirudha V. Sumant[δ], Silvino Bastos[‡], Brittany O'Neal[†], Thomas Mather[‡], and Anupama B. Kaul[†‡]
[†]Dept. of Materials Science and Engineering, University of North Texas, [δ]Center for Nanoscale Materials, Argonne National Laboratory, [‡]Dept. of Electrical Engineering, University of North Texas

Abstract

Monolayer transition metal dichalcogenides (TMDs), including WSe_2 often show unique and exciting optical and electrical features. WSe_2 is well-suited for high-performance optoelectronic devices, such as photodetectors due to its intense photoluminescence properties. This study investigates the production of monolayer WSe_2 using vapor growth approaches and subsequently the fabrication of optoelectronic devices manufactured using low-cost optical lithography. The monolayer membranes were synthesized using low-pressure chemical vapor deposition (LPCVD), which is a method for growing high-quality crystals on dielectric substrates. The use of halide salts allowed tungsten trioxide precursor reduction at lower temperatures, which improved the crystal formation process. Raman and photoluminescence spectroscopy revealed the monolayer nature of the synthesized WSe_2. Raman peaks were prominent and intense photoluminescence occurred at 1.60 eV. Optical lithography was used to create patterned features onto the monolayer membranes to yield electrical contacts for probing the devices at cryogenic temperatures. The ability to form such devices from monolayer WSe_2 through a low-cost, high-throughput approach, such as via conventional optical lithography should readily facilitate the demonstration of a wide-variety of novel and emergent devices. In this work, we will delve further into the optoelectronic properties of our manufactured WSe_2 photodetector devices with Ti contacts to evaluate their performance under various experimental conditions.

BIO: Utsab Kafley is a Ph.D. student in the Department of Materials Science and Engineering at University of North Texas (UNT), in the nanoscale materials and devices laboratory where his research is dedicated to advancing the field of 2D materials. After earning an MSc in Physics, Utsab pursued his passion for cutting-edge research in materials science, focusing on the fabrication of 2D materials through chemical vapor deposition (CVD) and their properties using Raman, photoluminescence spectroscopy, atomic force microscopy, scanning electron microscopy, and optoelectronic transport measurements. His current research investigates the nature of defects in 2D materials, such as oxygen complexes, doping-induced defects, as well as vacancy clusters, where emission characteristics are modulated for the creation of quantum emitters. Utsab is especially interested in the quantum properties of these materials, exploring how their unique characteristics can lead to innovative applications in next-generation electronic devices and quantum computing platforms.

Planarization of Single Crystal Diamond Surface via Atomic Layer Etching

Chandler Lewis[1,3], Michael Huerta[1,3], Jude Abunabaa[2,3], Anirudha Sumant[3], Ralu Divan[3], Anupama Kaul[2], and Yuankun Lin[1]

[1]Department of Physics, University of North Texas, [2]Department of Electrical Engineering, University of North Texas, [3]Center for Nanoscale Materials, Argonne National Laboratory

Abstract

Single Crystal Diamond, with its exceptional mechanical, electrical, and optical properties, holds significant potential as a substrate in semiconductor and quantum computing applications. However, defects and impurities commonly found on chemically vapor-deposited (CVD) diamond surfaces can limit their functionality. This study investigates the use of Atomic Layer Etching (ALE) as a novel planarization technique to smooth single crystal diamond (SCD) surfaces. A homoepitaxial CVD diamond sample underwent a strain relief reactive ion etch (RIE) followed by 1000 cycles of an ALE recipe using Ar/Cl_2 gas chemistry. Surface roughness and morphology were characterized using atomic force microscopy (AFM), while Raman spectroscopy assessed bonding structure and crystallinity. Preliminary results indicate a reduction in root-mean-square (RMS) roughness by approximately 40%, achieving a value of 0.6 nm, while retaining high crystallinity with a sharp Raman peak at 1332 cm^{-1}. Further experiments, including selective etching with masks and step-height characterization, are planned to refine the technique and expand its applications in nanofabrication.

BIO: Chandler Lewis is an undergraduate physics student at the University of North Texas, graduating in December 2024. His research focuses on materials science and nanotechnology. Chandler has completed two internships at the Center for Nanoscale Materials at Argonne National Laboratory, where he contributed to advancing Atomic Layer Etching (ALE) methodologies for planarizing single crystal diamond surfaces. His work also includes cleanroom operations, atomic force microscopy (AFM) characterization, reactive ion etching (RIE), and Raman spectroscopy.

At UNT, Chandler's research examines the photoluminescence and lifetimes of perovskite materials for solar cells. He is also passionate about leveraging his materials science expertise to address challenges in interdisciplinary fields, including medical physics, where innovative material solutions can have transformative impacts. Chandler values collaborative research and effective science communication, aiming to foster innovation at the intersection of fields.

Perovskite Solar Cell Stability Influenced by Collector Electrode and Alternative Hole Transport Materials

Sujan Aryal[1], and Anupama B. Kaul[1,2]
[1]Department of Electrical Engineering, University of North Texas, Denton, TX 76207, U.S.A.
[2]Department of Materials Science and Engineering, University of North Texas, Denton, TX 76207, U.S.A.

Abstract

Perovskite solar cells (PSCs) have garnered considerable attention in the photovoltaics (PV) community, driven by their remarkable rise in power conversion efficiencies (PCEs) exceeding 25%. However, challenges related to long-term moisture stability and material costs remain significant barriers to their commercialization. A critical issue lies in the use of 2,2′,7,7′-Tetrakis[N,N-di(4-methoxyphenyl)amino]-9,9′-spirobifluorene (spiro-OMeTAD) as the hole transport layer (HTL), which is prone to the formation of pinholes that compromise device stability, particularly in moisture-rich environments. Since the performance of PSCs relies on the integrity of each layer within the stack, defects such as pinholes in the HTL can lead to substantial degradation across the entire device. In this study, we investigate the stability of PSCs by exploring two aspects within the solar cell stack, which includes the role of the electrode materials, Ag versus Au, and potential for replacing Spiro with an alternate HTL. In the first, we show the impact of the electrode collector layer, specifically Ag and Au, on the degradation mechanism associated with the $MAPbI_3$ and a triple cation absorber, $Cs_{0.05}FA_{0.79}MA_{0.16}PbI_{2.45}Br_{0.55}$. Notably, Au-based PSCs for both absorbers in an n-i-p architecture showed superior PCE over Ag-based PSCs, where the optimized PCE of $MAPbI_3$ and triple cation-based PSCs was 15.39% and 18.21%, respectively. On the other hand, optimized PCE of $MAPbI_3$ and triple cation-based PSCs with Ag electrodes was 3.02% and 16.44%, respectively. In addition, the Ag-based PSCs showed a rapid decrease in PCE over Au-based PSCs through operational stability measurements. A quenching in the PL peak in the case of Ag-contacted $MAPbI_3$ provided direct evidence of the Ag corrupting the optical properties of the absorber through the formation of AgI which our X-ray diffraction (XRD) results confirmed. This was supported by the fact that an emission peak was still present in the triple cation Ag-device. For the Au-contacted $MAPbI_3$ the presence of a well-defined PL peak, though attenuated from the triple cation Au-device, suggested the AuI does not quell the emission spectrum for either the triple cation or the $MAPbI_3$ absorber. In the second case, we have initiated studies in considering alternative HTLs for potential replacement of the spiro-OMeTAD, with inorganic hole transport materials (HTMs) using solution-exfoliated two-dimensional (2D) transition metal dichalcogenide (TMDCs). The TMDC-based HTL was integrated with triple-cation perovskite absorbers in the solar cell stack and compared to spiro-OMeTAD-based devices.

BIO: Dr. Sujan Aryal graduated with his PhD in electrical engineering at the University of North Texas, specializing in advanced sensor technologies, 2D material-based logic electronics, and perovskite-based solar cells within the “More Moore” and “More than Moore” domains. As a member of the Nanoscale Materials and Devices Lab, Sujan has pioneered innovations in enhancing the stability of perovskite solar cells and advancing RF-based wireless temperature and humidity sensing, utilizing 2D dielectric materials to achieve significant improvements over conventional resistive sensors. His expertise spans design, fabrication, and characterization, with a strong foundation in CMOS-compatible logic circuits. Sujan has also developed automated processes using Python for experimental control and data acquisition, significantly improving efficiency in his research. His background in AI and robotics, stemming from undergraduate projects on machine learning for plant disease detection and an autonomous robotic vehicle, further enriches his skill set. Sujan has published multiple peer-reviewed journal papers, one book chapter, and more than 10 conference proceedings which include oral presentations at international conferences such as SPIE, TMS, TechConnect, as well as poster presentations at IEEE MetroCon, contributing meaningfully to novel materials, semiconductor technology, and device integration.

Dr. Sujan Aryal

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Exploring Light and Photonics: A 5E Model for Inquiry-Based Learning about Fiber Optic Cables

Samad Virani
University of Texas at Arlington

Abstract

This project investigates teaching photonics through hands-on demonstrations and explorations of light behavior. Beginning with a "Laser in a Bottle" demonstration, students observe how light follows a stream of water, illustrating principles of reflection and refraction. This setup introduces the concept of the critical angle and total internal reflection, key to understanding fiber optics. Students engaged in further activities using prisms and graphing light paths, allowing them to explore and visualize these concepts. Following the exploration, students will be introduced to Snell's law and practice using it to find the refractive index of specific materials. Ending this first day students will brainstorm explanations for the reason why the "laser in a bottle" demo is able to work and share it within small groups. The next day students will explore the use of fiber optic cables in data transfer. By tracing the development and applications of fiber optic cables, students are able to connect physics principles with real-world uses in communication technology. Throughout the lesson, students evaluate the efficiency and limitations of fiber optics and reflect on the advantages they offer over traditional communication methods. This interactive approach not only deepens comprehension of wave behaviors but also highlights the role of photonics in modern communication, preparing students to appreciate the science and engineering behind everyday technology.

BIO: Samad Virani holds a Bachelor of Science in Physics from the University of Texas at Arlington. Passionate about fostering scientific curiosity and preparing students for college, Virani began teaching chemistry at Uplift Luna Preparatory, an IB charter school dedicated to college readiness. Along with teaching, as the coach for the FRC robotics team, he actively engages students in hands-on STEM learning and is leading an initiative to expand STEM extracurriculars across the uplift network. Currently, Virani is piloting a physics course at his campus, working to enhance STEM education opportunities and cultivate the next generation of innovators.

Chemical Vapor Deposition for Nonlinear Photonic Device Fabrication

Brittany O'Neal[1,4], Utsab Kafley[1], Silvino Bastos[2], Steve Kamau[3,4], Yuankun Lin[3], Ihab El-Kady[4] and Anupama Kaul[1,2]

[1]Department of Materials Science and Engineering, University of North Texas; [2]Department of Electrical Engineering, University of North Texas; [3]Department of Physics, University of North Texas; [4]Sandia National Laboratories, Albuquerque, NM 87185, U.S.A.

Abstract

Chemical vapor deposition (CVD) is widely used in the synthesis of thin films for a variety of applications. Chief among these are films for optoelectronic devices. The overall goal of this study is to utilize low pressure CVD (LPCVD) in the production of thin films for nonlinear photonic applications. Meta-atoms will be modelled in MIRaGE, software developed by Sandia National Labs for designing photonic crystals, and then grown using CVD and characterized using Raman and optical microscopy to confirm their properties. First, however, it is important to understand the mechanisms behind growth and the procedures for effective utilization of LPCVD synthesis. As its name suggests, pressures below 10 Torr are utilized during the growth phase. Chemical precursors are heated to their sublimation points and react in the gas phase. Carrier gases transport reactants and products to the substrate where deposition can occur in various shapes and sizes. Experimentally observed shapes included triangles, hexagons, anvils, arrows, and stars. Maximum end-to-end shape size was around 84 μm for regular growth parameters and 124 μm when hydrogen continued to flow after the initial growth phase. This indicates hydrogen is beneficial to the continued growth and coalescence of the crystallites.

BIO: Brittany O'Neal was born to an electrical engineer and grew up with a fascination of science in all its forms, especially the natural sciences. She is deeply interested in the fundamentals of existence and is keenly fond of anything related to them. In particular, she is addicted to contemplating the interplay between matter, energy, gravity, the nuclear forces, and time. While her knowledge about these topics is currently somewhat lacking, she has a thirst for such knowledge and relishes every technical journal article she can find that discusses them. Originally studying to become an electrical engineer in the Pacific Northwest, she instead found herself at a technical college in Texas where she earned her associate of applied science degree with a 4.0 and, unsurprisingly, a membership in Phi Theta Kappa. She currently holds a Bachelor of Science in Materials Science and Engineering from the University of North Texas and is working on her master's degree in the same field and school.

Room Temperature 2D/3D Heterojunction Rectifiers Through Integration of Monolayer n-MoS_2 With p-type Boron Doped Diamond

Akshay Wali[1,2], Roshan Padhan[2], Ralu Divan[1], Pierre Darancet[1], Nihar Pradhan[2], and Anirudha V. Sumant[1]

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[2]*Layered Materials and Device Physics Laboratory, Department of Chemistry, Physics and Atmospheric Science, Jackson State University, Jackson, MS 39217, USA*

Abstract

Diamond has historically been considered as a promising material for developing high voltage and extreme condition power electronic devices. The promise stems from its remarkable properties which include superior thermal conductivity and large electric field strength in addition to high carrier mobilities. Despite having a well-established p-type doping scheme, diamond lacks a stable and reliable *n*-type doping method at room temperature which has impeded any promising advancements in diamond-based electronics. Since the donor energy levels are situated deep within the bandgap, any device operation can only happen at significantly higher temperatures where the deep donors are thermally activated. Here, we circumvent this bottleneck by integrating for the first time, atomically thin *n*-type two-dimensional (2D) monolayers of molybdenum disulfide (MoS_2) acting as a pseudo delta-doped layer with boron doped *p*-type polycrystalline and single crystal diamond to demonstrate both lateral and vertical 2D/3D heterostructure based *p-n* junction diodes, respectively, which operate at room temperature. From the measured current-voltage (I-V) curves, our two-terminal devices show an ideality factor [Equation] value of 6, a rectification ratio (RR) of 10^3, a reverse saturation current [Equation] of 1nA, and a [Equation] ratio of ~ 10^8. Moreover, our *p-n* heterojunction can seamlessly operate at temperatures as high as 573K, without any degradation in the device characteristics due to diamond's high thermal conductivity, which allows it to serve as an excellent heat sink. We also provide a discussion on the origin of the current rectification which primarily stems from tunnelling assisted interlayer recombination of majority carriers from the metal/2D junction into bulk diamond on application of forward bias voltage. We believe our demonstration can provide a holistic platform for the development of highly reliable and efficient diamond-based electronics integrated with low-dimensional materials.

BIO: Dr. Akshay Wali is a postdoctoral resident associate at Argonne National Laboratory in collaboration with Jackson State University as a joint appointee. He completed his PhD from Pennsylvania State University in December 2023 where he worked on developing information security primitives by exploiting the non-idealities in field effect transistors (FETs) that are typically found at the interface between two-dimensional (2D) materials and the gate oxide. At Argonne National Laboratory, he is working with Dr. Anirudha Sumant, group leader of nanofabrication devices (NFD) group with a focus on integration of 2D materials with single crystal (SC) and polycrystalline (PC) diamond for high voltage and power efficient devices and mechanisms

Synthesis and Characterization of Functionalized Heterostructures for Photodetection of Wse_2 for Photoabsorbers made with Scalable Fabrication Approaches

Silvino Bastos and Anupama B. Kaul
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Abstract

Semiconducting transition metal dichalcogenides (TMDCs) have been a topic of interest shortly after the initial exploration on mechanically exfoliated graphene exactly two decades ago. Similarly to graphene, the TMDCs have similar attributes such as interlayer coupling via the weak van der Waals interaction, and their high surface-to-volume ratio, particularly in the limit of monolayer membranes. The hybridization of these materials with lower dimensionality systems such as semiconducting quantum dots has shown enhancements in the optoelectronic behavior of the native material. In this work, we synthesized WSe_2 using a halide-assisted chemical vapor deposition approach which yielded membranes up to 100 μm linear dimensions. We then performed photolithography on these vapor-synthesized membranes to integrate them into photo-absorbing devices using a manual mask aligner and an UV-light head, unlike most prior approaches which typically use cost-prohibitive electron-beam lithography. This was then followed by electrode deposition using a standard physical vapor deposition process. The device was characterized at room temperature using broadband light and tuneable lasers and then hybridized using 0D CdTe quantum dots. The use of functionalized heterostructures made from these semiconducting 2D materials allows for the potential to realize high-performance, low-cost optoelectronic devices for future imaging and detector applications.

BIO: Silvino Pedrosa Bastos is an electrical engineer and automation systems specialist currently pursuing his Ph.D. at the University of North Texas. He holds a degree in Electrical Engineering from the Universidade Federal da Bahia (2021) and a qualification in Automation Systems from the Instituto Federal da Bahia (2011). Silvino's recognitions include securing first place in the poster competition at the 2023 edition of the IEEE Metrocon.

University of North Texas (UNT) and Argonne Workshop Logistics Coordinators' Biographies

Ms. Allyson Tesky (UNT)

Allyson Tesky is a Ph.D. student being mentored by Dr. Anupama Kaul at the University of North Texas (UNT). She completed her Bachelor of Science and Master of Science in Biomedical Engineering in 2023 and 2024, respectively, with minors in math, computer science, and electrical engineering, and now continues the research she started in her undergraduate career, as a Ph.D. student. She received the UNT Outstanding Graduating Masters Student Award from the Department of Biomedical Engineering in 2024. With a focus on graphene and non-toxic inks, Allyson's research explores the possibility of graphene electrodes as a long-wear alternative to traditional wet electrodes. Moreover, her interest in sustainability extends beyond the lab to her activities with the Society of Ecological Restoration at UNT and the Texas Master Naturalists—a joint venture between Texas Parks and Wildlife and Texas A&M focused on conservation of our natural resources. Allyson has also participated in several other academic and service-orientated societies including IEEE – Eta Kappa Nu, Alpha Eta Mu Beta, and Phi Theta Kappa.

Ms. Lynnean Celmer (Argonne)

Lynnean Celmer is an accomplished event planner and communications professional with extensive experience in managing large-scale meetings, conferences, and corporate events. She currently serves as an Event Planner at Argonne National Laboratory, where she directs and manages scientific conferences, workshops, and seminars, ensuring compliance with Department of Energy policies and enhancing stakeholder engagement. Lynnean leverages advanced tools like Cvent and mobile apps to streamline event registration, and logistics all while staying budget-conscious and eco-friendly.

Previously, Lynnean held pivotal roles at Tyson Foods, Hillshire Brands, Sara Lee Food & Beverage, and Alberto Culver. She has managed multimillion-dollar budgets, orchestrated national meetings for up to 1,200 attendees, and implemented innovative communication strategies to enhance user engagement and organizational effectiveness. Her expertise spans event logistics, content management, intranet design, and team collaboration, with certifications in Cvent Event Management, Hybrid and Mobile Events. A graduate of DePaul University with a Bachelor of Science in Marketing, Lynnean has been recognized for her academic excellence and leadership. Her volunteer work includes special needs adult ministry, therapy dog sessions, and youth ministry leadership. She enjoys traveling, crafting, and all things Disney. Lynnean is skilled in Microsoft Office and various event management technologies, making her a versatile and detail-oriented professional passionate about creating memorable and impactful experiences.

Mr. Min Hong (Argonne)

Min Hong is an administrative assistant in Nanoscience and Technology, where he supports Ani Sumant and several others on their scientific research at the Center of Nanoscale Materials location. He has been at Argonne for about a year and a half. He has a bachelor's degree in human resources and before Argonne, worked at JP Morgan Chase bank as a Loan Processor.

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Allyson Tesky is a Ph.D. student being mentored by Dr. Anupama Kaul at the University of North Texas (UNT). She completed her Bachelor of Science and Master of Science in Biomedical Engineering in 2023 and 2024, respectively, with minors in math, computer science, and electrical engineering, and now continues the research she started in her undergraduate career, as a Ph.D. student. She received the UNT Outstanding Graduating Masters Student Award from the Department of Biomedical Engineering in 2024. With a focus on graphene and non-toxic inks, Allyson's research explores the possibility of graphene electrodes as a long-wear alternative to traditional wet electrodes. Moreover, her interest in sustainability extends beyond the lab to her activities with the Society of Ecological Restoration at UNT and the Texas Master Naturalists—a joint venture between Texas Parks and Wildlife and Texas A&M focused on conservation of our natural resources. Allyson has also participated in several other academic and service-orientated societies including IEEE – Eta Kappa Nu, Alpha Eta Mu Beta, and Phi Theta Kappa.

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Dr. Yaowu Hao is a professor in the Department of Materials Science and Engineering (MSE) at the University of Texas at Arlington. He received his Ph. D. degree from MIT in 2003 and his MS degree from University of Florida in 1998, both in MSE. He was a postdoctoral fellow in the Department of Materials Science and Engineering at Johns Hopkins University before he joined UT Arlington in Fall 2005. He earned Bachelor and Master of Science degrees in Metal Physics and Chemistry at the University of Science and Technology in Beijing. His research interests include Nanotechnology, Nanomedicine, and Nuclear Medicine. A total of over $3M funding from federal and state agencies such as NSF, NIH and Cancer Prevention and Research Institute of Texas (CPRIT) has been secured to support his research endeavors. He has published 72 papers in referred scientific journals and holds 2 issued US patents. Under his supervision, 9 PhD and 10 MS students have graduated.

Rasool Kenarangui
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Dr. Rasool Kenarangui is a member of the research group at the Energy Systems Research Center, at the University of Texas at Arlington. From 1976 to 1980 he worked as a research associate at Science Application Inc., in Ames Iowa, USA. From 1980 to 1995 Dr. Kenarangui was a Professor in the Electrical Engineering Department of the University of Tabriz, in Iran. He was Visiting Professor in the Electrical Engineering Department at the University of Waterloo in Ontario, Canada from 1988–1989. His areas of interest is power systems analysis and operation, power plants and nuclear power generation, reliability analysis, application of fuzzy logic and control in electric power systems, computer simulation of electric power systems and load forecasting.

8.0 References

[1] K. S. Novoselov, A. K. Geim, S. V. Morozov, D. Jiang, Y. Zhang, S. V. Dubonos, I. V. Grigorieva, and A. A. Firsov, "Electric field effect in atomically thin carbon films," *Science* **306**, 666 (2004).

[2] K. Novoselov, D. Jiang, F. Schedin, T. J. Booth, V. V. Khotkevich, S. V. Morozov, A. K. Geim, and T. M. Rice, "Two-dimensional atomic crystals.," *Proc. of the Natl. Academy of Sciences USA* **102**, 10451 (2005).

[3] A. K. Geim and I. V. Grigorieva, "Van der Waals heterostructures," *Nature* **499**, 419 (2013).

[4] J. Bardeen and W. H. Brattain, "The transistor, a semiconductor triode," *Phys. Rev.* **74**, 230 (1948).

[5] W. H. Brattain and J. Bardeen, "Nature of the forward current in Germanium point contacts," *Phys. Rev.* **74**, 231 (1948).

[6] K. P. O'Brien, C. H. Naylor, C. Dorow, K. Maxey, et al. "Process integration and future outlook of 2D transistors," *Nat. Commun.* **14**, 6400 (2023).

[7] K. F. Mak, C. Lee, J. Hone, J. Shan and T. F. Heinz, "Atomically thin MoS2: a new direct-gap semiconductor," *Phys. Rev. Lett.* **105**, 136805 (2010).

[8] S. Lukman, L. Ding, L. Xu, Y. Tao, A. C. Riis-Jensen, G. Zhang, Q. Y. S. Wu, M. Yang, S. Luo, C. Hsu, L. Yao, G. Liang, H. Lin, Y. W. Zhang, K. S. Thygesen, Q. J. Wang, Y. Feng, and J. Teng, "High oscillator strength interlayer excitons in two-dimensional heterostructures for mid-infrared photodetection," *Nat. Nanotechnol.* **15**, 675 (2020).

[9] I. Aharonovich, D. Englund, and M. Toth, "Solid-state single-photon emitters," *Nat. Photon.* **10**, 631(2016).

[10] X. Liu and M. C. Hersam, "2D materials for quantum information science," *Nature Reviews Materials* **4**, 669 (2019).

[11] CHIPS for America Act: https://www.govinfo.gov/content/pkg/PLAW-117publ167/pdf/PLAW-117publ167.pdf; https://www.congress.gov/bill/116th-congress/house-bill/7178

[12] National Photonics Initiative, *Enabling American Innovation, Competition and Security, Recommendations by the National Photonics Initiative (NPI),* (2017); available at https://www.lightourfuture.org/

[13] National Quantum Initiative, *National Strategic Overview for Quantum Information Science*, (2018); available at https://www.quantum.gov/

[14] 2015 NSF US-EU Workshop Final Report: https://engineering.unt.edu/mse/research/labs/nmdl/files/USEUWSR15.pdf

[15] 2016 NSF EU-US Workshop Final Report: https://engineering.unt.edu/mse/research/labs/nmdl/files/EUUSWSR16.pdf

[16] NSF AFOSR Workshop on 2D Materials and Devices Beyond Graphene, 2012: https://nsf2dworkshop.rice.edu/

[17] NSF's Emerging Frontiers in Research and Innovation (EFRI), *2-Dimensional Atomic-layer Research and Engineering (2-DARE)* initiative, NSF 13-583 (Kaul served as Lead and Topic Coordinator, cumulative funding of > $50 Million); replaced by NSF 16-502.

[18] Dear Colleague Letter issued in 2016, https://www.nsf.gov/pubs/2016/nsf16102/nsf16102.jsp?org=ENG for supplemental funding,

as an outcome of the "*NSF US-EU Workshop on 2D Layered Materials and Devices,"* held in 2015, Arlington, VA (Kaul served as Workshop Chair/PI on NSF Workshop Proposal).

[19] The European Commission's Graphene Flagship Program launched in 2013: https://graphene-flagship.eu/

[20] NSF EFRI, *2-Dimensional Atomic-layer Research and Engineering (2-DARE)* initiative: NSF 13-583, NSF 16-502.

[21] Platform for the Accelerated Realization, Analysis, and Discovery of Interface Materials (PARADIM) at Cornell University, Ithaca, NY, funded through the NSF Materials Innovation Platform (MIP) since 2016: https://www.paradim.org/

[22] 2D Crystal Consortium (2DCC) at Penn State University, University Park, PA, funded through the NSF Materials Innovation Platform (MIP) since 2016: https://www.mri.psu.edu/2d-crystal-consortium

[23] Institute for Basic Science (IBS), Center for 2D Quantum Heterostructures at Sungkyunkwan University (SKKU), Seoul, South Korea: https://www.ibs.re.kr/2dqh/

[24] D. De Fazio, D. G. Purdie, A. K. Ott, P. Braeuninger-Weimer, T. Khodkov, S. Goossens, T. Taniguchi, K. Watanabe, P. Livreri, F. H. L. Koppens, S. Hofmann, I. Goykhman, A. C. Ferrari, and A. Lombardo, "High-mobility, wet-transferred graphene grown by chemical vapor deposition," *ACS Nano* **13**, 8926 (2019).

[25] K. Thodkar and F. Gramm, "Enhanced Mobility in Suspended Chemical Vapor-Deposited Graphene Field-Effect Devices in Ambient Conditions," *ACS Applied Materials & Interfaces* **15**, 37756 (2023).

[26] N. Georgoulea, N. M. Caffrey, and S. R. Power, "One-dimensional topological channels in heterostrained bilayer graphene," *Phys. Rev. B* **109**, 035403 (2024).

[27] K. F. Mak and J. Shan, "Photonics and optoelectronics of 2D semiconductor transition metal dichalcogenides," *Nat. Photonics* **10**, 216 (2016).

[28] E. C. Regan, D. Wang, E. Y. Paik, Y. Zeng, L. Zhang, J. Zhu, A. H. MacDonald, H. Deng, and F. Wang, "Emerging exciton physics in transition metal dichalcogenide heterobilayers," *Nat. Rev. Mater.* **7**, 778 (2022).

[29] N. Bernhardt, S. Kim, J. E. Fröch, S. J. U. White, N. M. H. Duong, Z. He, B. Chen, J. Liu, I. Aharonovich, and A. S. Solntsev, "Large few-layer hexagonal boron nitride flakes for nonlinear optics," *Opt. Lett.* **46**, 564 (2021).

[30] H. J. Conley, B. Wang, J. I. Ziegler, R. F. Haglund, S. T. Pantelides, and K. I. Bolotin, "Bandgap engineering of strained monolayer and bilayer MoS2," *Nano Lett.* **13**, 3626 (2013).

[31] K. He, C. Poole, K. F. Mak, J. Shan, "Experimental demonstration of continuous electronic structure tuning via strain in atomically thin MoS2," *Nano Lett.* **13**, 2931 (2013).

[32] A. S. Bandyopadhyay, A. B. Puthirath, P. M. Ajayan, H. Zhu, Y. Lin, and A. B. Kaul, "Intrinsic and strain-dependent properties of suspended WSe_2 crystallites toward next generation nanoelectronics and quantum-enabled sensors," *ACS Appl. Mater. Interfaces* **16***,* 3640 (2024).

[33] F. Koppens, T. Mueller, P. Avouris et al., "Photodetectors based on graphene, other two-dimensional materials and hybrid systems," *Nat. Nanotech.* **9**, 780 (2014).

[34] A. R. Tesky, M. Hicks, S. Aryal, J. Molitor, B. Jones, J. Molitor, and A. B. Kaul, *"*Dry Electrodes with a Printed Cellulose-Graphene Ink for Low-Profile Strain Sensors in Electromyography," *J. Materials Chem. C* **13**(14), 7004 (2025).

[35] A. Wali, R. Padhan, R. Divan, L. Stan, N. Pradhan, and A. V. Sumant, "Heterogeneous integration of boron-doped p-diamond with monolayer n-MoS_2 for PN junctions operating at room temperature," *Nano Letters* **25**, 15353 (2025).

[36] S. Aryal, A. B. Puthirath, B. Jones, A. S. R. Bati, B. Chen, T. Mather, P. M. Ajayan, E. H. Sargent, and A. B. Kaul, "Solution-processed tungsten diselenide as an inorganic hole transport material for moisture-stable perovskite solar cells in the n-i-p architecture," *Sol. Energy Materials and Solar Cells* **282**, 113313 (2025).

[37] Q. Wu, G. Zhao, H. Wu, and M. Zhang, "Open-ended exploration of ultrashort pulse lasers: an innovative design strategy for devices based on 2D materials," *Photon. Res.* **11**, 1238 (2023).

[38] H. Shan, L. Lackner, and B. Han, E. Sedov, C. Rupprecht, H. Knopf, F. Eilenberger, J. Beierlein, N. Kunte, M. Esmann, K. Yumigeta, K. Watanabe, T. Taniguchi, S. Klembt, S. Höfling, A. V. Kavokin, S. Tongay, C. Schneider, and C. Antón-Solanas, "Spatial coherence of room-temperature monolayer WSe_2 exciton-polaritons in a trap," *Nat. Commun.* **12**, 6406 (2021)

[39] Y. Jiang, S. Chen, W. Zheng, B. Zheng, and A. Pan, "Interlayer exciton formation, relaxation, and transport in TMD van der Waals heterostructures," *Light.: Sci. Appl.* **10**, 72 (2021).

[40] A. W. Elshaari, W. Pernice, K. Srinivasan, O. Benson, and V. Zwiller, "Hybrid integrated quantum photonic circuits," *Nat. Photonics* **14**, 285 (2020).

[41] M. Toth and I. Aharonovich, "Single Photon Sources in Atomically Thin Materials," *Annu. Rev. Phys. Chem*. **70**, 123 (2019).

[42] Y. Arakawa and M. J. Holmes, "Progress in quantum-dot single photon sources for quantum information technologies: A broad spectrum overview," *Appl. Phys. Rev* **7**, 021309 (2020).

[43] M. Atatüre, D. Englund, N. Vamivakas, S.-Y. Lee, and J. Wrachtrup, "Material platforms for spin-based photonic quantum technologies," *Nat. Rev. Mater.* **3**, 38 (2018).

[44] J.-H. Kim, S. Aghaeimeibodi, J. Carolan, D. Englund, and E. Waks, "Hybrid integration methods for on-chip quantum photonics," *Optica* **7**, 291 (2020).

[45] S. Wehner, D. Elkouss, and R. Hanson, "Quantum internet: a vision for the road ahead," *Science* **362**, 6412 (2018).

[46] D. D. Awschalom, R. Hanson, J. Wrachtrup, and B. B. Zhou, "Quantum technologies with optically interfaced solid-state spins," *Nat. Photonics* **12**, 516 (2018).

[47] M. Y. Toriyama, J. Zhan, S. Kanai, and G. Galli, "Strategies to search for two-dimensional materials with long spin qubit coherence time," npj 2D Materials and Applications **9**, 108 (2025).

[48] A. B. Kaul, Y. Wang, A.P- Li, X. Li, and X. Ma, "Single photon emitters in van der Waals solids for quantum photonics: materials, theory and molecular-scale characterization probes," *J. Physics D: Applied Physics* **58**, 1230001 (2025).

[49] M. W. Doherty, N. B. Manson, P. Delaney, F. Jelezko, J. Wrachtrup, and L. C. Hollenberg, "The nitrogen-vacancy colour centre in diamond," *Phys. Rep.* **528**, 1 (2013).

[50] L. Weston, D. Wickramaratne, M. Mackoit, A. Alkauskas, and C. G. Van de Walle, "Native point defects and impurities in hexagonal boron nitride," *Phys. Rev. B* **97**, 214104 (2018).

[51] C. Chakraborty, L. Kinnischtzke, K. M. Goodfellow, R. Beams, and A. N. Vamivakas, "Voltage-controlled quantum light from an atomically thin semiconductor," *Nat. Nanotechnol.***10**, 507 (2015).

[52] A. Srivastava, M. Sidler, A. V Allain, D. S. Lembke, A. Kis, and A. Imamoğlu, "Optically active quantum dots in monolayer WSe_2," *Nat. Nanotechnol.***10**, 491 (2015).

[53] Y.-M. He, G. Clark, J. R. Schaibley, Y. He, M.-C. Chen, Y.-J. Wei, X. Ding, Q. Zhang, W. Yao, X. Xu, C.-Y. Lu, and J.-W. Pan, "Single quantum emitters in monolayer semiconductors," *Nat. Nanotechnol.***10**, 497 (2015).

[54] M. Koperski, K. Nogajewski, A. Arora, V. Cherkez, P. Mallet, J.-Y. Veuillen, J. Marcus, P. Kossacki, and M. Potemski, "Single photon emitters in exfoliated WSe2 structures," *Nat. Nanotechnol.* **10**, 503 (2015).

[55] P. Tonndorf, R. Schmidt, R. Schneider, J. Kern, M. Buscema, G. A. Steele, A. Castellanos-Gomez, H. S. J. van der Zant, S. M. de Vasconcellos, and R. Bratschitsch, "Single-photon emission from localized excitons in an atomically thin semiconductor," *Optica* **2**, 347 (2015).

[56] T. T. Tran, C. Elbadawi, D. Totonjian, C. J. Lobo, G. Grosso, H. Moon, D. R. Englund, M. J. Ford, I. Aharonovich, and M. Toth, "Robust multicolor single photon emission from point defects in hexagonal boron nitride," *ACS Nano* **10**, 7331 (2016).

[57] T. T. Tran, K. Bray, M. J. Ford, M. Toth, and I. Aharonovich, "Quantum emission from hexagonal boron nitride monolayers," *Nat. Nanotechnol.* **11**, 37 (2016).

[58] G. Grosso, H. Moon, B. Lienhard, S. Ali, D. K. Efetov, M. M. Furchi, P. Jarillo-Herrero, M. J. Ford, I. Aharonovich, and D. Englund, "Tunable and high-purity room temperature single-photon emission from atomic defects in hexagonal boron nitride," *Nat. Commun.* **8**, 705 (2017).

[59] A. Gottscholl, M. Kianinia, V. Soltamov, S. Orlinskii, G. Mamin, C. Bradac, C. Kasper, K. Krambrock, A. Sperlich, M. Toth, I. Aharonovich, and V. Dyakonov, "Initialization and read-out of intrinsic spin defects in a van der Waals crystal at room temperature," *Nature Materials* **19**, 540 (2020).

[60] A. R. P. Montblanch, D. M. Kara, I. Paradisanos, C. M. Purser, M. S. G. Feuer, E. M. Alexeev, L. Stefan, Y. Qin, M. Blei, G. Wang, A. R. Cadore, P. Latawiec, M. Loncar, S. Tongay, A. C. Ferrari, and M. Atatüre, "Confinement of long-lived interlayer excitons in WS2/WSe2 heterostructures," *Commun. Phys.* **4**, 119 (2021).

[61] H. Baek, M. Brotons-Gisbert, Z. X. Koong, A. Campbell, M. Rambach, K. Watanabe, T. Taniguchi, and B. D. Gerardot, "Highly energy-tunable quantum light from moiré-trapped excitons," *Sci. Adv.* **6**, 8526 (2020).

[62] S. M. Hus and An-Ping Li, "Spatially-resolved studies on the role of defects and boundaries in electronic behavior of 2D materials," *Progress in Surface Science* **92**, 176 (2017).

[63] Y. Zhang, M. A. Hossain, K. J. Hwang, P. F. Ferrari, J. Maduzia, T. Pena, S. M. Wu, E. Ertekin, and A. M. van der Zande, "Patternable process-induced strain in 2D monolayers and heterobilayers," *ACS Nano* **18**, 4205 (2024).

[64] The International Roadmap for Devices and Systems (IRDS) (2021): *More Moore*. https://irds.ieee.org/images/files/pdf/2021/2021IRDS_MM.pdf

[65] L. Wu, "The next generation of gate-all-around transistors," *Nature Electronics* **6**, 469 (2023).

[66] M. C. Lemme, D. Akinwande, C. Huyghebaert, and C. Stampfer, "2D Materials for future heterogeneous electronics," *Nature Comm*. **13**, 1392 (2022).

[67] European Commission's Graphene Flagship 10 Year Assessment Report (2024): https://digital-strategy.ec.europa.eu/en/library/graphene-flagship-10-years-assessment

[68] The Graphene Flagship-Graphene Flagship Launches First European Experimental Pilot Line: https://graphene-flagship.eu/materials/news/graphene-flagship-launches-first-european-epl

[69] Summary of Workshop on Quantum Recruitment in the Federal Government: https://www.quantum.gov/wp-content/uploads/2022/01/Summary-QIS-Fed-Workforce-JAN2022.pdf

[70] Intel Invests $100M in Ohio and National Semiconductor Education and Research: https://download.intel.com/newsroom/archive/2025/en-us-2022-03-17-intel-invests-100m-in-ohio-and-national-semiconductor-education-and-research.pdf

[71] C. Roncaioli, C. A. Hart, R. Walsworth, D. P. Fahey, "All-in-one quantum diamond microscope for sensor characterization," *AVS Quantum Science* **6**, 044403 (2024).

[72] P. Sohr, P. Koller, S. Ecker, *et al.* "Quantum communication networks with defects in silicon carbide," preprint arXiv:2403.03284 (2024)

[73] J. R. Toledo, D. B. de Jesus, M. Kianinia, A. S. Leal, C. Fantini, L. A. Cury, G. A. M. Safar, I. Aharonovich, and K. Krambrock, "Electron paramagnetic resonance signature of point defects in neutron-irradiated hexagonal boron nitride," *Phys. Rev. B* **98**, 155203 (2018).

[74] Z. Lin, A. McCreary, N. Briggs, *et al.*, "2D materials advances: from large scale synthesis and controlled heterostructures to improved characterization techniques, defects and applications," *2D Materials* **3**, 042001 (2016).

[75] P. Ares and K. S. Novoselov, "Recent advances in graphene and other 2D materials," *Nano Materials Science* **4**, 3 (2022).

[76] B. Luo, G. Liu, and L. Wang, "Recent advances in 2D materials for photocatalysis," *Nanoscale* **8**, 6904 (2016).

[77] A. Jain, *et al.* "The Materials Project: A materials genome approach to accelerating materials innovation," *APL Materials* **1**, 011002 (2013).

[78] K. T. Butler, D. W. Davies, H. Cartwright, O. Isayev, and A. Walsh, "Machine learning for molecular and materials science," *Nature* **559**, 547 (2018).

[79] P. M. Sadler, G. Sonnert, Z. Hazari, and R. Tai, "The role of advanced high school coursework in increasing STEM career interest," *Science Educator* **23**, 1 (2014).

[80] National Academy of Engineering and National Research Council, "*Community Colleges in the Evolving STEM Education Landscape: Summary of a Summit*," Washington, DC: The National Academies Press (2012).