Materials - Synthesis & Characterization

AI-Empowered Automatic 2D Material Image Sampling and Scoring System

M.-C. Chen, A.-Y. Lu, S. Liu, J. Kong
Sponsorship: SRC JUMP 2.0 SUPREME Center

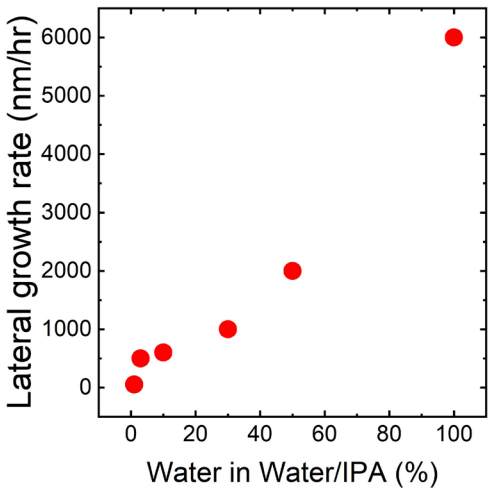
As the miniaturization of transistors progresses, the inherent physical limitations of silicon-based semiconductors, including leakage current, short-channel effect, and carrier mobility, are beginning to surface. Two-dimensional (2D) materials present a promising solution for further downsizing while preserving control over electronic properties. In the development of 2D materials, precise process control of chemical vapor deposition (CVD) is critical to the outcome, and our group has leveraged machine learning (ML) to expedite the process in several aspects, including literature text mining, recipe optimization, and unraveling correlation between Raman and photoluminescence spectra. For recipe optimization of our autonomous CVD synthesis platform, it is important to provide reliable feedback of CVD results to the recipe optimization algorithm. In this project, we aim to design an AI-empowered automatic 2D material image sampling and scoring system that can capture optical images of the 2D materials from CVD substrates, thereby avoiding human bias in selecting better crystals. The scope of this automated system starts at navigation of the linear motion stage to transferring the sample under the microscope, perform fine autofocus along the z-axis, taking images according to strategically designed sampling pattern and executing vignetting correction and stitching, all the way through image recognition with FastSAM, pattern statistics, and generating a final single score for each experimental result. Multiple independent functions including linear stage control, sample edge and angle detection, image processing, and FastSAM crystal recognition have been completed, and we are currently working on system integration. This system will enhance the integration of automatic characterization branch for our autonomous CVD platform and accelerate the further development of 2D materials.

Seeding Promoter Effect on Metal Organic Chemical Vapor Deposition Synthesized Molybdenum Disulfide

Y. Jiao, J. Zhu, T. Palacios
Sponsorship: Center for Heterogeneous Integration of Micro Electronic Systems (JUMP 2.0)

Two-dimensional (2D) transition metal dichalcogenide (TMD) materials are promising for next-generation electronics thanks to their excellent electronic and photonic properties. Metal organic chemical vapor deposition (MOCVD) has gained significant research interest for its excellent uniformity and quality. Many factors such as flow rate, temperature, and substrate conditions affect its growth quality. Optimization of the growth recipe is often difficult. Seeding promoters such as NaCl have been reported to significantly improve the growth rate and quality. However, a systematic understanding of the mechanism behind this improvement is yet to be quantitatively investigated. Understanding the effect of seeding promoters can benefit the optimization of growth recipes and lead to better uniformity of 2D material deposition process over large area substrates, which is one of the biggest limitations of the large-scale fabrication of 2D electronics.

Here, we quantitatively studied NaCl's promoting effect on the high temperature MOCVD growth of MoS_2. The study investigates the concentration dependence of the seeding density, flake size, and flake quality of as-grown MoS_2 and proposes the mechanism of NaCl's promoting effect. This study also discusses the trade-off and contamination issues of utilizing seeding promoters. With this result, we further optimized the growth and improved the material uniformity across the 200-mm platform as well as boosting the average mobility to around 50 $cm^2/(V \cdot s)$. This effort has provided insight into the fundamental growth mechanism and suggests a promising future of heterogeneous integration of TMD material and complementary metal-oxide semiconductor technology.



▲ Figure 1: Lateral growth rate change based on NaCl concentration in saturated water:isopropyl alcohol solution.

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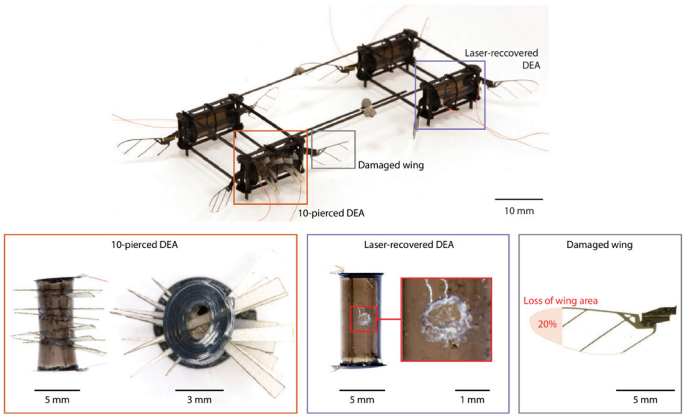
Laser-assisted Failure Recovery for Dielectric Elastomer Actuators in Aerial Robots

S. Kim, Y-H. Hsiao, Y. Lee, W. Zhu, Z. Ren, F. Niroui, Y. Chen
Sponsorship: NSF, MathWorks Fellowship

Dielectric elastomer actuators (DEAs) are a class of muscle-like soft actuators that are widely applied in many robotic systems demonstrating robustness against unexpected damage–a distinguishing feature that is challenging to achieved in robots with rigid actuators. However, unlike natural muscles, DEAs are prone to suffering local dielectric breakdowns. These often cause global device failure, limiting the performance, lifetime, and size scalability of DEA-based systems. Here, we developed an isolation process of defects or damages on DEAs (Figure 1) that directly cause local breakdowns. We first investigated the electromechanical evolution of external damage as the DEAs break down. Then, we designed a simplified material testing setup that can imitate piercing damages to optimize the fabrication of DEAs. Finally, we internally isolated the damaged area from original actuator structure. As a result, our DEAs can endure over 100 punctures while maintaining high bandwidth (>400 Hz) and power density (>700 W/kg) – sufficient for supporting energetically expensive locomotion such as flight.

Moreover, when the DEAs suffered severe dielectric breakdowns that cause device failure, we demonstrated a laser-assisted repair method for isolating the critical defects and recovering performance. We performed the ablation using diode-pumped solid-state laser that penetrates the transparent elastomer layer while partially degrading the electrode layer material. Then, we applied high voltage input to the actuator to electrically disconnect the ablated region from surrounding actuation area. We finally achieved 12-second controlled hovering flight with a 4-unit robot driven by pierced and laser-recovered DEAs along with the damaged wing (Figure 2). This laser-assisted repair technique demonstrates precise localization and isolation of critical defects, effectively decoupling actuator size from the probability of experiencing such defects. Consequently, our laser-assisted repair method enables the fabrication of considerably larger DEAs, thereby expanding the scope of applications across diverse domains. These findings culminate in the first aerial robot that can endure critical actuator and wing damage without compromising flight quality.

▲ Figure 1: A conceptual photograph illustrating a damaged biomimetic flying robot module that landed on a cactus.



▲ Figure 2: 760-mg flapping-wing micro aerial robot consisting of four modules that can endure severe piercing and burning damages on DEAs and having the tip of the wing cut off while maintaining controlled flight capability.

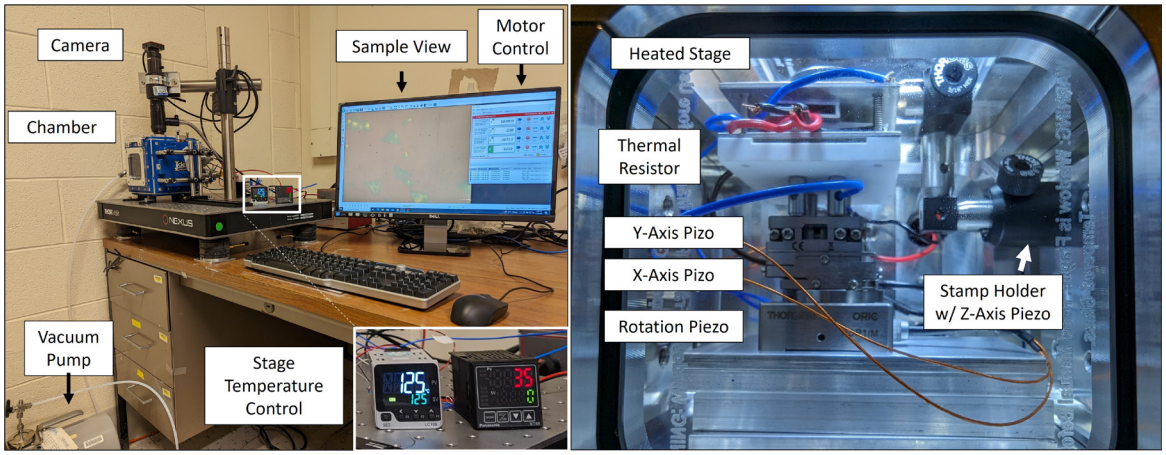
FURTHER READING

- S. Kim, Y-H. Hsiao, Y. Lee, W. Zhu, Z. Ren, F. Niroui, and Y. Chen. "Laser-assisted Failure Recovery for Dielectric Elastomer Actuators in Aerial Robots," *Science Robotics*, eadf4278, Mar. 2023.

Striving for Rapid Fabrication of Arbitrary, Ultraclean 2D Heterostructures using a Robotic Vacuum Transfer Setup and Automation

Z. Hennighausen, S. He, J. Wang, X. Zheng, T. Zhang, K. Zhang, K.Y. Ma, Z. Wang, J. Park, J. Kong
Sponsorship: US Army Research Office (grant number W911NF2210023), US Army Research Office through the Institute for Soldier Nanotechnologies at MIT (under cooperative agreement No. W911NF-18-2-0048).

Stacking two-dimensional (2D) materials into heterostructures facilitates the emergence of new properties, including superconductivity, interlayer excitons, and ferroelectricity, thereby enabling revolutionary new devices. Specialized transfer setups are required to fabricate 2D heterostructures with clean interfaces. Despite successes of the current technology, they require near-constant user engagement and a large time investment, thereby limiting throughput. To mitigate these challenges, we built a robotic transfer setup that operates in vacuum to reduce gas bubbles and improve interface cleanliness. We plan to identify ideal transfer parameters and fabricate 2D heterostructures with minimal user engagement using automation and machine learning. We plan to synergize the setup with materials grown in our group (e.g., graphene, hBN, TMDs, SnSe) and across MIT to fabricate increasingly complex heterostructures to advance technology in numerous areas (e.g., optics, electronics, qubits).



▲ Figure 1: Image of robotic vacuum transfer setup. (Right) Inside vacuum cube. Piezos enable x, y, z, and twist-angle control.

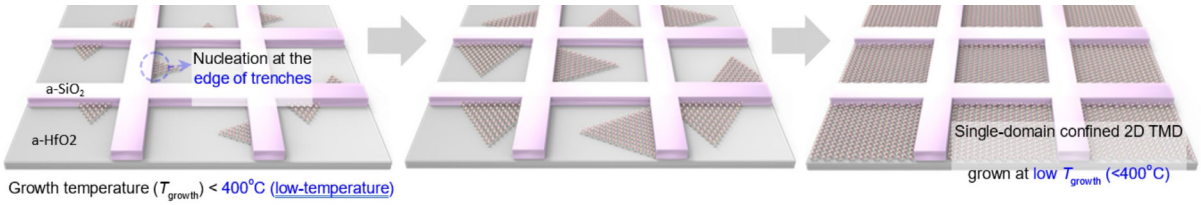
Non-epitaxial Growth of Single-crystalline Transition Metal Dichalcogenides at Low Temperature for Silicon Back-end-of-line Integration

D. Lee, K. Kim, S. Seo, J. Kim
Sponsorship: Samsung

Two-dimensional (2D) Transition Metal Dichalcogenides (TMDs) have been highlighted as a channel material for next generation electronics beyond Moore's law. However, their integration with conventional silicon technology has been a critical hurdle to commercialization because of their high growth temperature.

In addition, even though wafer scale growth of MoS_2 below the back-end-of-line (BEOL) temperature limit has been reported recently, its performance is not comparable to conventional silicon devices because the material is polycrystalline. Furthermore, WSe_2 growth below the BEOL limit has never been demonstrated, which is essential for the p-type devices needed to realize 2D CMOS circuits.

In this work, we overcome those challenges and demonstrate non-epitaxial single-crystalline growth of both MoS_2 and WSe_2 on an amorphous HfO_2 coated substrate below 400℃. We demonstrate that using our technique, their electrical performances are comparable to materials grown at high temperatures.

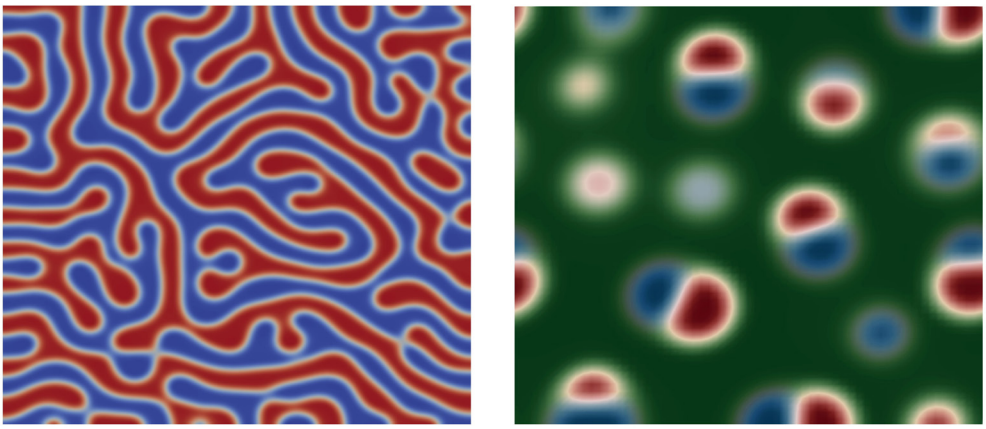


▲ Figure 1: The dangling bonds at the edge of SiO_2 trenches facilitate the nuclei formation even at low growth temperature. In addition, the trenches physically confine the extra lateral growth of single domain TMDs to prevent grain boundaries.

Continuum-Scale Modeling Strategies for Microstructure Formation and Evolution

P. K.Inguva, R.D. Braatz
Sponsorship: A*STAR

Understanding the formation and evolution of microstructures is of immense interest for engineering the properties and performance of advanced materials in a variety of applications. Phase-field models (PFMs) provide a convenient and extensible framework for studying multiphase and multi-component systems at length and time-scales otherwise inaccessible to meso- and molecular-scale methods such as molecular dynamics. PFMs introduce and track the evolution of one or more auxiliary variables (the phase field) whose values specify which phase is in each spatial location in the system at a given time. Depending on the application, PFMs can be solved by themselves or coupled to additional species, momentum, and energy conservation equations to suitably describe the physics of the process/system. The descriptive capabilities of PFMs have resulted in their widespread use in many areas of science and engineering including fluid dynamics, solidification, fracture mechanics, structure formation, and tumor growth modeling. The use of PFMs across multiple disciplines has resulted in relevant advances often being siloed, taking time to be disseminated across the literature. In this work, a framework for systematically conceptualizing PFMs (and their various extensions) is first outlined to inform their use and development. Subsequently, multiple case studies of increasing physical and computational complexity are presented to demonstrate the capabilities and limitations of using PFMs. All code for numerical simulations and additional details on the mathematics and physics of PFMs will be made available on a public GitHub repository. The developed resources will help accelerate the use of computational methods for developing advanced nanomaterials.



▲ Figure 1: Exemplar phase-field simulations of a binary (left) and ternary (right) polymer blends.

Mixed-dimensional Integration of 3D Complex-oxides on 2D Materials via Remote Epitaxy

J.-E. Ryu, S. Lee, K. S. Kim, X. Zhang, C. S. Chang, M.-K. Song, J. Kim
Sponsorship: IARPA (6948435)

A novel method for growing single crystalline three-dimensional (3D) complex-oxide layers on atomically thin graphene interlayer, known as remote epitaxy, has been proposed as the future of heterogeneous integration strategies. The technique enabled growth of high-quality thin film and perfect transfer of the grown film. However, However, the transfer of graphene, which is a typical process for forming a graphene interlayer on growth substrates, inevitably induces a significant number of unwanted defects such as wrinkles, holes, process residues, and interfacial contamination. Such defects can disturb the remote interaction between the substrate and epitaxial layer through graphene, reducing the crystal quality and exfoliation yield of membranes. Recently, we developed a direct synthesis method for growing alternative two-dimensional (2D) materials, such as transition metal dichalcogenides (TMDs), on growth substrates, which enables the creation of wafer-scale, defect-free 2D interlayers for reliable remote epitaxy of high-quality spinel $CoFe_2O_4$ (CFO) and garnet $Y_3Fe_5O_{12}$ (YIG) thin films. The atomically clean van der Waals interfaces formed by direct growth of TMDs onto growth substrates serve as an ideal platform for high-throughput production of single-crystalline, freestanding complex-oxide membranes that can be released from substrates, but also for facile fabrication of a new class of mixed-dimensional heterogeneous systems that exhibit emergent physical phenomena at well-defined 3D/2D heterointerfaces. Based on this unique approach to integrating mixed-dimensional heterostructures in a scalable and controlled manner, we demonstrate new device concepts that take advantage of unusual physical coupling or decoupling at exotic 3D/2D interfaces, which are both fundamentally intriguing and practically useful.

Controllable Vapor-phase Growth of Multilayer h-BN on Insulator

K. Zhang, Z. Hennighausen, H. Liu, J. Park, J. Kong
Sponsorship: U. S. Army Research Laboratory, U. S. Army Research Office (under contract/grant number W911NF2320057)

Multilayer hexagonal boron nitride (h-BN) is highly desirable as an ideal 2D insulator for the fabrication of two-dimensional (2D) van der Waals (vdW) heterostructures and superior electronic/ optoelectronic devices. However, achieving controllable synthesis of high-quality, large-area multilayer h-BN films, ranging from a few to dozens of layers, remains a challenge. Here, we employ a vapor-phase growth method to synthesize large-area multilayer h-BN films directly on insulator substrates (such as quartz or sapphire), using a Fe-Ni-B (Fe-B) alloy and nitrogen gas as precursors. The Fe-Ni-B alloy serves a dual purpose: it provides the boron source and catalyzes the reaction with nitrogen to form h-BN at a high temperature. Furthermore, we use an ice-assisted method to transfer the grown multilayer h-BN films onto arbitrary target substrates, thereby avoiding contamination from polymers or chemical agents. The outcome of the research efforts here will enable us to construct large-area, high-performance 2D functional heterostructures and devices.

Synthesis of Single-Crystal hBN Multilayers on Ni (111)

K. Y. Ma, Z. Hennighausen, J. Kong
Sponsorship: U.S. Army Research Laboratory, U.S. Army Research Office (contract/grant number W911NF2320057)

Two-dimensional hexagonal boron nitride (hBN) has been demonstrated to be the "ideal" dielectric substrate for 2D materials-based field effect transistors (FETs) – offering the potential for extending Moore's law using the superior electronic properties of these novel nanomaterials. Although hBN thicker than a monolayer is more desirable as substrate for 2D semiconductors, the growth of highly uniform and single-crystal few- or multi-layer hBN has not yet been demonstrated. Previously, K. Y. Ma et. al [1] developed the epitaxial growth of wafer-scale single-crystal tri-layer hBN by a chemical vapor deposition method. Uniformly aligned tri-layer hBN islands were found to grow on a 2 cm x 5 cm single-crystal Ni (111) at an early stage of growth and finally to coalesce into a single-crystal film. Cross-sectional transmission electron microscopy (TEM) results showed that a $Ni_{23}B_6$ interlayer is formed (during cooling) between the single-crystal tri-layer hBN film and Ni (111) substrate by boron dissolved in Ni (111) and that there is an epitaxial relationship between tri-layer hBN and $Ni_{23}B_6$ and between $Ni_{23}B_6$ and Ni (111). The tri-layer hBN film was found to act as a protective layer that remains intact during catalytic evolution of hydrogen – suggesting continuous and uniform single-crystal tri-layer hBN in large area. This tri-layer hBN was transferred onto the SiO_2 (300 nm)/Si wafer acting as a dielectric layer to reduce electron doping from the SiO_2 substrate in MoS_2 FETs. In this project, we will build upon the previous findings to achieve high-quality few-layer hBN for various applications.

FURTHER READING

- [1] K. Y. Ma, L. Zhang, S. Jin, Y. Wang, S. I. Yoon, H. Hwang, J. Oh, D. S. Jeong, M. Wang, S. Chatterjee, G. Kim, A-R. Jang, J. Yang, S. Ryu, H. Y. Jeong, R. S. Ruoff, M. Chhowalla, F. Ding, and H. S. Shin, "Epitaxial Single-crystal Hexagonal Boron Nitride Multilayers on Ni (111)", *Nature 606*, 88-93 (2022)

Amorphous 2D Materials – A Novel Platform for Remote Epitaxy and Nanopatterned Epitaxy of III-V Semiconductors with Low Decomposition Temperatures

K. Lu, N. M. Han, H. Kim, Y. Liu, S. H. Cho, J. Kim
Sponsorship: AFRL (FA9453-18-2-0017 and FA9453-21-C-0717), DARPA (029584-00001), DOE (DE-EE0008558), Umicore

Optoelectronic devices based on indium phosphide (InP), such as telecomm lasers, offer outstanding properties that outperform Silicon-based counterparts. However, the cost of InP wafers is considerably higher compared to commonly used semiconductor wafers. While reusing original wafers can effectively reduce costs, traditional techniques for wafer recycling, such as chemical lift-off, introduce significant expenses during fabrication, negating the cost savings achieved through wafer reuse. Consequently, the reuse of InP wafers becomes challenging but with significant opportunity, and new techniques are needed to scalably and cheaply produce InP membranes for optoelectronics.

Remote epitaxy and nanopatterned epitaxy have emerged as novel methods capable of facilitating the growth of InP with high quality, as well as enabling easy exfoliation of the InP films. These breakthroughs offer a promising avenue for cost-effective wafer reuse with the introduction of an interlayer of Two-dimensional (2D) materials between the epilayer and the substrate. Here we report the growth of amorphous boron nitride (a-BN) on InP wafers at low temperature that enabled improved quality of InP epitaxial membranes and their perfect exfoliation. We show fully covered a-BN on InP despite the low decomposition temperatures of InP substrates. The surface of a-BN coated InP substrate remains smooth with a RMS roughness of around 3 Å. We also demonstrate 100% coverage of single-crystal InP membranes grown on a-BN, with the film's quality remaining high. Through this low temperature molecular beam epitaxy (MBE) growth approach with remote epitaxy and nanopatterned epitaxy, we successfully demonstrate large-scale flexible InP membrane exfoliation and recycling of InP substrates, which will lead to new opportunities in InP membrane-based optoelectronics and novel heterostructures with significantly reduced cost.

Spike Timing Dependent Plasticity in Electrochemical Ionic Synapses

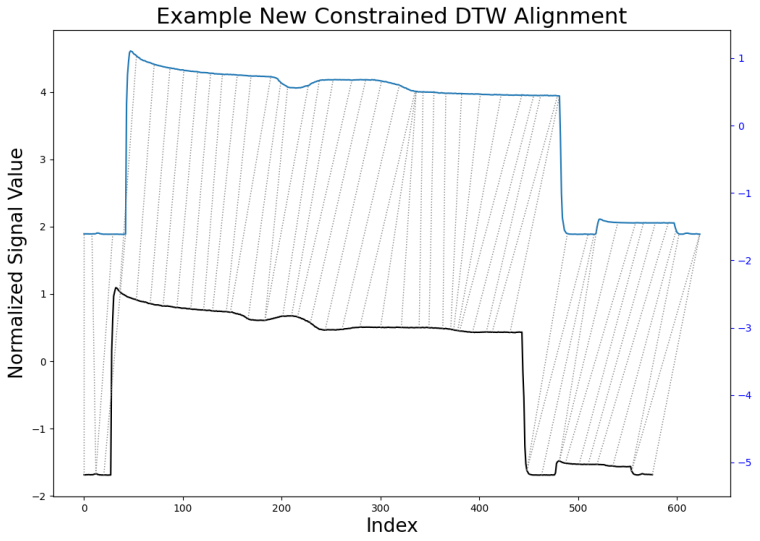
M. Huang, J. A. del Alamo, J. Li, B. Yildiz
Sponsorship: MIT Quest for Intelligence Program

Spiking neural networks (SNNs) have emerged as a promising architecture for machine intelligence due to their potential for highly efficient computation. However, realizing these networks in hardware presents unique challenges, particularly regarding the development of programmable synaptic devices capable of achieving time-dependent weight updates. Electrochemical ionic synapses (EIS) provide a promising solution, with their high energy efficiency, low variability, and rich ionic dynamics. In this work, we leverage the strong nonlinearity of EIS to implement various forms of spike-timing-dependent plasticity (STDP), a fundamental mechanism underlying learning in biological systems. Our results showcase STDP timescales ranging from milliseconds to nanoseconds, enabling high computing throughput. By designing appropriate pre- and post-synaptic neuron signals, we demonstrate that different forms of the STDP function can be deterministically predicted and emulated. Additionally, heterogeneous STDP within an array can be realized, where synapses from a single pre-neuron connecting to different post-synaptic neurons can exhibit distinct learning rules. Furthermore, we observe lower variability compared to existing hardware STDP implementations. Overall, our findings suggest that EIS could enable highly efficient SNN hardware implementations with high throughput. We believe this would further advance the development of bio-inspired computing and intelligent systems.

Dynamic Time Warping Constraints for Semiconductor Processing

R. Owens, F. Sun, C. Venditti, D. Blake, J. Dillon, D. S. Boning
Sponsorship: Analog Devices, Inc.

Semiconductor fabrication monitoring has become increasingly complex, and nonlinear variations in signal timing have made anomaly detection more difficult. We present a new method for preprocessing semiconductor sensor signals that improves anomaly detection model performance. The proposed method uses dynamic time warping (DTW) and semiconductor processing domain knowledge to address the problem of nonlinear signal alignment. New constraints for the DTW algorithm are developed based on semiconductor processing recipe steps. In tests using the kernel density estimation (KDE) fault detection method on labelled plasma etch datasets, the new constraints consistently outperform comparison methods. This demonstrates the usefulness of DTW, and specifically the new DTW constraints, as a preprocessing method for semiconductor sensor signals used in anomaly detection.

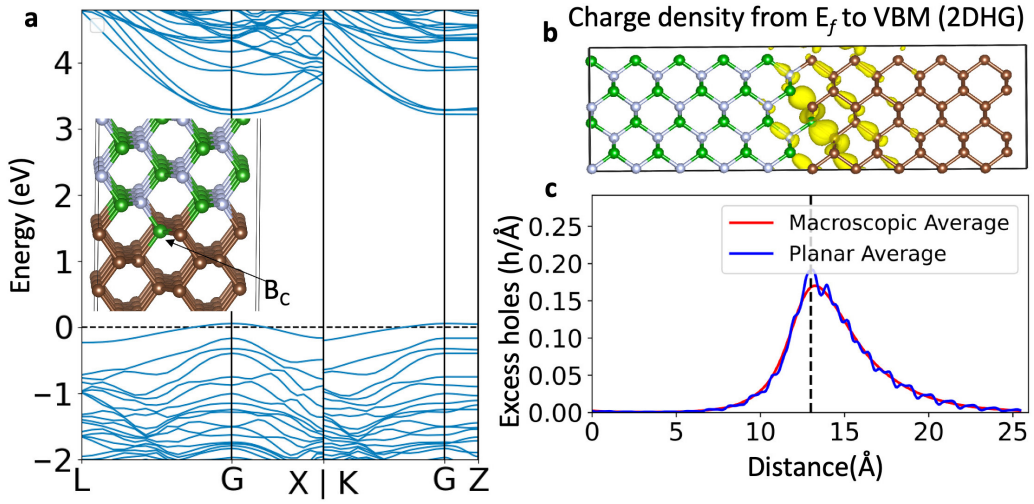


▲ Figure 1: Alignment of two optical endpoint signals. The grey dotted lines indicate mappings between the signals which were generated using the proposed constraints on the DTW algorithm.

Understanding the Role of Defects at Diamond/cBN Interface: A First-principles Study

S. Saini, K. J. Tibbetts, M. J. Polking, B. Yildiz
Sponsorship: MIT Lincoln Laboratory for Cubic BN/Diamond Heterostructures for High-Power RF Electronics

Diamond and cubic boron nitride (c-BN) stand out in high-power electronics due to their wide band-gap, and high thermal conductivity. Despite advancements in epitaxial c-BN growth on diamond, optimizing carrier mobility at the c-BN/diamond interface is impeded by a limited knowledge of the impacts of defects. Our first-principles study investigates the diamond/c-BN interface, focusing on crystal orientation, defects, and doping effects on electronic properties. We found that intrinsic defects, BC and CN, induce p-type doping and lead to 2D hole gas (2DHG) formation, BC case is shown in Fig.1. The electron-deficient nature of these defects and the type-II band alignment are crucial for 2DHG formation. Our work highlights the importance of defect engineering in enhancing the performance of diamond-based electronic devices.



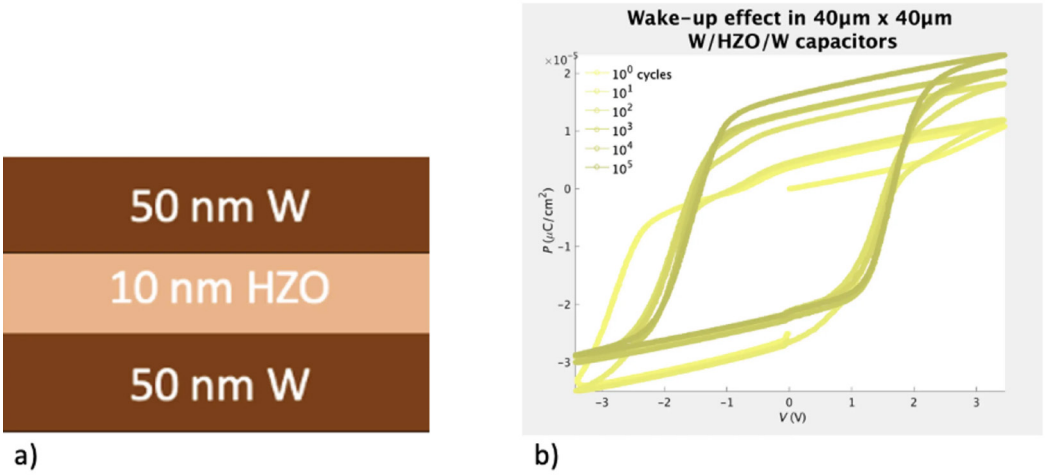
▲Figure 1: (a) Electronic band structure of BC defect at the diamond/c-BN(110) interface. (b) Charge density distribution, and (c) excess holes from Fermi level to valence band maximum.

Endurance Characterization of Ferroelectric Hafnium Zirconium Oxide for Memory Applications

T. E. Espedal, Y. Shao, E. R. Borujeny, J. A. del Alamo
Sponsorship: MIT UROP, Intel Corporation, Semiconductor Research Corporation

To realize on-chip next-generation AI accelerators, 3D monolithic integration of non-volatile memory (NVM) on CMOS is highly favored. Among different NVW technologies, ferroelectric (FE) memory based on CMOS-compatible hafnium zirconium oxide (HZO) has emerged as one of the most promising, as it could potentially provide low-voltage operation, fast switching, long data retention, and high device endurance. Understanding the detailed ferroelectric polarization switching physics in HZO thin films is of great importance for potential memory applications.

In working towards developing high-endurance back-end-of-line (BEOL) ferroelectric NVM technology, we investigate the endurance property of HZO in metal/FE/metal (MFM) structures that have been prepared with a variety of material stacks and fabrication parameters. We have studied unique physics in FE-HZO, including wake-up, fatigue, and breakdown, by carrying out repeated polarization-voltage measurements with carefully designed voltage pulse patterns. Through correlation with HZO fabrication parameters and materials characterization, we expect to better predict prospects and limitations of HZO in applications to future FE memory devices.



▲ Figure 1: a) Schematic diagram of W/HZO/W structure: 50 nm W / 10 nm HZO / 10 nm W b) Evolution of polarization-voltage (P-V) loop with increasing numbers of switching pulses applied.

Formation of Monolayer Metal Oxides via Room Temperature Conversion of Two-Dimensional Transitional Metal Dichalcogenides

X. Zheng, P. Wu, A. Penn, Z. Wang, T. Zhang, X. Zhong, J. Wang, J. Park, S. Xie, A. Kahn, D. Schlom, J. Kong
Sponsorship: SRC

Two-dimensional (2D) materials have attracted significant interest due to their ultra-thin thickness and quantum confinement effect. Despite the rich and diverse library of discovered 2D materials, the investigation on 2D oxides has been limited. There is a demand for atomically thin oxides because their band gaps are usually in the range of 3-6 eV, a range less accessible using the most studied 2D materials, such as graphene, transitional metal dichalcogenides (TMDCs) or h-BN. Here, by using 2D TMDCs as templates and converting them to oxide, we show that wafer-scale amorphous oxides can be directly formed at room temperature. The oxidation is enabled by UV light-generated ozone, which is a mild, controllable and homogeneous process. The properties of the as-converted transitional metal oxide monolayers are explored using optical, electrical and electron microscopic approaches. We further explored the potential applications of molybdenum oxide monolayers in two-dimensional field effect transistors. This strategy can be easily extended to a variety of metal oxides, enabling future development of metal oxides in the quantum regime.

Low Temperature Wafer-scale Synthesis of 2D TMD Material for Back-end-of-line Heterogeneous Integration

Y. Jiao, J. Zhu, T. Palacios
Sponsorship: Center for Heterogeneous Integration of Micro Electronic Systems (JUMP 2.0)

Two-dimensional (2D) transition metal dichalcogenide (TMD) materials have demonstrated promising future in the next generation of highly scaled microelectronic devices for their excellent electronic and photonic properties such as high mobility, direct bandgap in combination with their atomic scale dimensions. These properties have also made 2D TMD materials ideal candidate for back-end-of-line (BEOL) integration process with silicon front-end integrated circuits (IC). However, the current method of transfer integration of 2D TMD material and Si IC potentially introduces damages and defects to the material, thus greatly impedes the performance of fabricated devices. Direct growth of TMD was proven difficult in BEOL process due to temperature limits (<400˚C)

In this work, we explore the low temperature large wafer-scale direct synthesis of high quality 2D TMD (MoS_2, $MoTe_2$, WSe_2, etc.) which are BEOL compatible. The Metal-Organic Chemical Vapor Deposition (MOCVD) system we designed is capable of direct growth on platforms up to 200 mm in diameter. The BEOL compatibility is achieved through separation of high temperature precursor decomposition region and low temperature deposition region. This enables monolayer TMD materials direct integration with Si front end devices without introducing damage, thus maintaining the optimal device performance. This integration technique shall bring a promising future of heterogeneous integration of TMD with various front-end substrates and applications in flexible electronics, optoelectronics and other monolithic 3D integration electronics.

High Indium Content InGaN Strain Relaxation

Y. Liu, B. Park, J. Kim, J. Kim
Sponsorship: Samsung

Light-emitting diodes (LEDs) are widely used in illumination and displays because of their high efficiency and brightness. Indium gallium nitride (InGaN) has been used as the material to make blue and green LEDs due to its tunable bandgap. However, in order to decrease the band gap of InGaN, more indium has to be incorporated into the material, leading to a high lattice mismatch between the InGaN layer and the GaN substrate. This mismatch decreases the quality of high indium content InGaN, which is an obstacle to the effective use of InGaN as the base material for RGB (red, green and blue) pixels. Here, we propose a method to fabricate high quality LEDs based on InGaN with high indium content using remote epitaxy. Conventionally, when an epilayer is grown on the substrate using epitaxial methods, the lattice structure of the epilayer always perfectly follows the lattice structure of the substrate by forming a covalent bond. Remote epitaxy, on the other hand, provides a way to copy the substrate lattice structure to a freestanding, non-covalently bonded thin film epilayer. When a layer of 2D material is deposited prior to the epilayer, the epilayer grown on the top of the 2D material still follows the crystalline structure of the substrate under the influence of the penetrated potential field from the substrate. However, unlike normal epitaxial methods, the epilayer spontaneously relaxes due to the slippery surface of the 2D material, attached by van der Waals forces rather than covalent bonding. Therefore, high quality InGaN can be obtained with this method. We demonstrate remote epitaxy of high-quality InGaN epilayers based on in-situ MBE-grown amorphous boron nitride (a-BN) as the release layer. By depositing InGaN on a-BN/GaN substrate, the misfit strain can be relaxed from the beginning of the growth regardless of the indium composition, enabling high-quality RGB LED pixels that can be used in superior electronic device displays.

Electric Field-induced Rapid Growth of Single-Crystal Graphene

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Chemical vapor deposition (CVD) has emerged as an effective method for the synthesis of high-quality and large area graphene. However, achieving rapid synthesis of high-quality, single-crystal graphene remains a challenge. Recent studies have shown that the synthesis of single-crystal, high-quality graphene is achievable utilizing 500 nm - 700 nm single-crystal Cu(111) film on sapphire as catalyst and substrate. Nevertheless, the severe evaporation of the thin copper film during high-temperature growth has always been an issue. It has been reported that applying electric field between the copper substrate and a counter electrode could accelerate graphene growth, which can significantly shorten the duration of exposure of thin Cu(111) film to high temperature. In our study, we combined these two methods to use their respective advantages for the rapid synthesis of single-crystal, high-quality graphene. We applied electric field to both low pressure and ambient pressure chemical vapor deposition of graphene, while using single-crystal Cu(111) film on sapphire as the catalyst and substrate. We aim to shorten the growth time for low pressure CVD to within five minutes, and for ambient pressure CVD to within thirty minutes, for growing complete single-crystal graphene film on Cu(111). We believe that this integrated method holds promise for enhancing the efficiency and accessibility of high-quality graphene synthesis.