CENIDE & WIN Seminar Series on 2D-MATURE

DFG IRTG 2803 & NSERC CREATE

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University of California, Berkeley

"Direct Integration of 2D Materials for Next Generation Electronic Devices"

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10:00 a.m. ET / 16:00 p.m. CET

Zak Al Balushi is an assistant professor in the department of Materials Science and Engineering at University of California, Berkeley, and a faculty scientist in the Materials Science Division at the Lawrence Berkeley National Laboratory. Zakaria received his B.S. (2011), M.S. (2012) in Engineering Science and his Ph.D. (2017) in Materials Science and Engineering all from The Pennsylvania State University. His early work focused on integration and fabrication of silicon nanowire devices, then on the growth of group-III nitride semiconductors, in situ metrology during MOCVD growth, epitaxial graphene and the discovery and characterization of unconventional low-dimensional materials and heterostructures. Prior to his appointment at the University of California, Berkeley, he held two postdoctoral fellowships: the Resnick Prize Fellowship in Applied Physics and Materials Science and the NSF Alliances for Graduate Education and the Professoriate (AGEP) Fellowship both at the California Institute of Technology under the supervision of Professor Harry Atwater. At the University of California, Berkeley, his research group continues to expand in this area and beyond, creating new synthesis and integration schemes for emerging low-dimensional materials. He is currently serving on the editorial board of Communications Materials, is an elected executive committee member for the American Association for Crystal Growth and recently named "Four rising stars who are reshaping nanoscience" by Nature [Nature 608, S12-S13 (2022)]. He is also a SK Hynix Faculty Fellow, Society of Hellman Fellow, a CIFAR Azrieli Global Scholar in Quantum Materials and a recipient of the NSF CAREER and Micron Corporation Early Career Awards in 2022.

Two-dimensional (2D) semiconductors, such as molybdenum disulfide (MoS2), are emerging as key materials for next-generation electronics, addressing challenges in the miniaturization of silicon-based technologies. Despite progress in scaling-up 2D materials, integrating them into functional devices remains challenging, particularly in the context of three-dimensional integration. In the first part of my talk, I will present a scalable method for growing high-quality mono- to few-layer MoS2 on large wafers using a spin-on precursor, molybdenum ethyl xanthate. This approach facilitates the formation of a metastable amorphous molybdenum trisulfide phase, which we can then be leveraged for direct heterogeneous integration. We thoroughly investigate the growth dynamics and associated versatile features using comprehensive characterization, reactive force-field molecular dynamics simulations, and Density Functional Theory. Our method allows precise control over film thickness, grain size, and defect density, yielding wafer-scale monolayer MoS2 with reliable optical properties comparable to as-exfoliated samples. Additionally, we achieve area-selective formation of MoS2 and the direct deposition of sub-5 nm high-k oxides using atomic layer deposition, without the need for seeding or surface functionalization. This process enables the fabrication of complex superlattice structures,

top-gated FETs, and memristor devices, all from a single-source chemistry. Our findings highlight the versatility of spin-on metal xanthate chemistries for the synthesis and integration of transition metal dichalcogenides (MoS2, WS2, NbS2, ReS2, etc.), paving the way for advanced nanoscale fabrication processes and enhancing the commercial viability of 2D materials in electronics.

Moreover, forming heavily doped regions in two-dimensional materials, like graphene, are a steppingstone to the design of emergent devices and heterostructures. In the second part of my talk, I will present a selective-area approach to tune the work-function and carrier density in monolayer graphene by spatially synthesizing sub-monolayer gallium beneath the 2D-solid. Localized metallic gallium is formed via precipitation from an underlying diamond-like carbon (DLC) film that was spatially implanted with gallium-ions. Controlling the interfacial precipitation process with annealing temperature allows for spatially precise ambipolar tuning of the graphene work-function that remains stable even in ambient conditions. Our theoretical studies corroborated the role of the gallium at the heterointerface on charge transfer and electrostatic doping of the graphene overlayer, with charge carrier densities from ~1.8×10^10 cm^(-2) (hole-doped) to ~7×10^13 cm^(-2) (electron-doped) as measured by in-situ and ex-situ measurements. The extension of this doping scheme to other implantable elements into DLC provides a new means of exploring the physics and chemistry of highly doped overlayed two-dimensional materials.

Finally, metalorganic chemical vapor deposition (MOCVD) has become a pivotal technique for developing wafer-scale TMD 2D materials. If time permits, I will discuss our recent findings on the impact of MOCVD growth conditions on achieving uniform and selective polymorph phase control of MoTe2 over large wafers. We demonstrated the controlled and uniform growth of few-layer MoTe2 in pure 2H, 1T', and mixed-phases at various temperatures on up to 4-inch C-plane sapphire wafers with hexagonal boron nitride templates. At 600oC, high-quality 2H-MoTe2 was obtained within a narrow temperature window, verified with absorption and TEM analysis. In addition, we observed strong exciton-phonon coupling effects in multiwavelength Raman spectroscopy when the excitation wavelength was in resonance with the C-exciton. Our findings indicate that temperature-induced Te vacancies play a crucial role in determining the MoTe2 phase. This study highlights the importance of precise control over the MOCVD growth temperature to engineer the MoTe2 phase of interest for device applications.