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Advanced Large-scale Manufacturing of 2D Materials

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Abstract: Metalorganic chemical vapor deposition (MOCVD) has emerged as the method for synthesizing wafer-scale films of transition metal dichalcogenide 2D materials, playing a significant role in the growth of these 2D semiconductors directly onto oxidized silicon (SiO_2) or sapphire substrates. This is followed by mechanical transfer onto processed silicon. However, there are several issues with this approach, as the development of reliable transfer techniques from the growth substrate to the device structure is neither trivial nor industrially scalable. Alternatively, solution processing techniques, such as spin coating, can rapidly produce consistent wafer-scale thin films. Most studies on the solution deposition of 2D materials have focused on spin-coating suspensions consisting of dispersed flakes produced via chemical exfoliation of a bulk crystal. Flake sizes range from several hundred nanometers to several microns. These flakes are not soluble in common solvents, and controlling flake size and thickness poses challenges. Consequently, thin films produced invariably consist of misaligned flakes with edge defects that impede transport characteristics in transistors. Other methods include the use of insoluble suspensions produced from precursor chemistries, typically transition metal trioxides. These are first dip-coated onto the desired substrate and decomposed in a chalcogen environment at temperatures exceeding 800 °C. However, this method is also incompatible with back-end-of-line (BEOL) or 3D heterogeneous integration. In this talk, I will discuss recent developments in my group, focusing on a process to produce fully soluble solutions from a unique xanthate molecule. This molecule can be dissolved in common solvents and spin-coated onto any substrate, including printed electrodes and polymers. Furthermore, it can be used within gate-all-around (GAA) 3D transistor structures for the fabrication of MoS_2 at temperatures as low as 250 °C. Our rapid synthesis process of large-area MoS_2 films, specifically in its monolayer form via spin coating, has not been demonstrated previously. This represents an important step toward the scalable synthesis of wafer-scale 2D semiconductor thin films without resorting to post-growth wafer transfer techniques. We also demonstrate that by using direct laser writing, we can create features of MoS_2 (as well as MoO_3 in air) by controlling the laser power and annealing environment. Our fabrication process showcases the feasibility of using a single-source chemical precursor to form monolayer 2D semiconductors with good transport characteristics and optical properties that improve with increasing crystallization temperatures. As a result, it can serve as a semiconductor in the channel of microelectronic transistor architectures in both BEOL and FEOL.

Bio: Dr. 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 Caltech, he focused on the synthesis and characterization of phase transformations in transition metal dichalcogenides 2D materials. 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 a Principal Editor for Journal of Materials Research, 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.