Nanostructure Synthesis and Fabrication
Room Tamna Hall B - Session NS-TuA

2D Materials and Devices

Moderators: Nathanaelle Schneider, CNRS-IPVF, **Tamar Segal-Peretz**, Israel Institute of Technology

4:00pm **NS-TuA-11 Towards Low-Resistance P-Type Contacts to 2D Transition Metal Dichalcogenides Using Plasma-Enhanced Atomic Layer Deposition***, **Ageeth Bol**,* University of Michigan, Ann Arbor **INVITED**

One major limitation of 2D transition metal dichalcogenide (TMD) based FETs is the high contact resistance between metallic electrodes and semiconducting channels, particularly for p-type contacts. In this presentation I will address how PEALD of p-type TMDs can be used to improve this contact resistance. First, I will go over controlled doping strategies to form p-type 2D TMD contact materials using PEALD, with an emphasis on Al doped MoS_2 [1] and Nb Doped WS_2 [2]. Our recent results show contact resistancevalues as low as 0.30 ± 0.26 kΩ·µm between Pd and PEALD $Nb_xW_{1-x}S_2$ [3], demonstrating that low resistance contacts between metal and p-type TMDs are possible. Then, I will discuss reducing unintentional p-doping introduced during PEALD of TMDs. PEALD TMDs typically contain some level of hydrogen impurities that leads to unintentional p-doping. We have shown that these impurities can be reduced by introducing an Ar plasma C step in the standard PEALD TMD process [4]. Finally, the use of remote plasmas in PEALD for contact deposition can lead to the creation of undesired impurities and defects in the 2D TMD channel, possibly impacting electronic behavior. I will present how adjustments to the PEALD process of WS_2 can reduce the impact of the plasma and maintains the integrity of the underlying TMD channels.

[1] V. Vandalon, M. A. Verheijen, W. M. M. Kessels, and A. A. Bol, "Atomic Layer Deposition of Al-Doped MoS2: Synthesizing a p-type 2D Semiconductor with Tunable Carrier Density," *ACS Appl. Nano Mater.*, vol. 3, no. 10, pp. 10200–10208, Oct. 2020, doi: 10.1021/acsanm.0c02167.

[2] J. J. P. M. Schulpen *et al.*, "Nb Doping and Alloying of 2D WS2 by Atomic Layer Deposition for 2D Transition Metal Dichalcogenide Transistors and HER Electrocatalysts," *ACS Appl. Nano Mater.*, vol. 7, no. 7, pp. 7395–7407, Apr. 2024, doi: 10.1021/acsanm.4c00094.

[3] R. Li *et al.*, Ultra-Low-Resistance Contacts to Heavily-Doped p-Type NbxW1-xSy Thin Films Grown by Atomic Layer Deposition. *ACS Appl. Mater. Interfaces,* 2025. Accepted.

[4] M. Mattinen *et al.*, "Toolbox of Advanced Atomic Layer Deposition Processes for Tailoring Large-Area MoS2 Thin Films at 150 °C," *ACS Appl. Mater. Interfaces*, vol. 15, no. 29, pp. 35565–35579, Jul. 2023, doi: 10.1021/acsami.3c02466.

4:30pm **NS-TuA-13 Selective Passivation of 2D TMD Surface Defects by Atomic Layer Deposition for Enhancing Recovery Rate of Gas Sensor***, **Minji Kim**, Inkyu Sohn, Dain Shin, Sangyoon Lee, Hwi Yoon, Jisang Yoo, Seung-min Jung, Hyungjun Kim,* Yonsei University, Korea

Two-dimensional transition metal dichalcogenides (2D TMDs) have gained significant interest as promising materials for gas sensors due to their high surface-to-volume ratio, high electron mobility, tunable band gap, and efficient sensing capabilities at room temperature.[1] However, commercialization of TMD gas sensors is currently limited by low recovery rates due to strong chemisorption of gas molecules on surface defects. Unfavorable desorption of gas molecule from defects hinders reliability and long-term stability of TMD gas sensor.[2] In this study, atomic layer deposition (ALD) is used to selectively passivate surface defects of MoS_2 and WS_2 gas sensors with Al_2O_3. SEM analysis confirms that Al_2O_3 are deposited only at defective sites such as grain boundaries and vacancies of MoS_2 and WS_2. As a result, Al_2O_3 passivated TMD gas sensor shows nearly complete recovery rate of 96% even at room temperature, which improved from 74% recovery rate of pristine TMD gas sensor. Also, passivated gas sensor shows higher response toward NO_2 gas compared to pristine gas sensor due to n-type doping effect of Al_2O_3 on TMD. This result shows that defect-selective passivation is a promising strategy to overcome low recovery rate of TMD gas sensor and enhance its sensing properties.

References

[1] Huo, N. et al., *Scientific reports* 4.1 (2014): 5209.

[2] K. Lee, R. et al., *Advanced materials* 25.46 (2013): 6699-6702.

4:45pm **NS-TuA-14 Beyond the conventional AB process: Advanced ALD approaches for controlling the properties and growth of MoS_2 and WS_2 2D Materials***, **Cindy Lam**, Eryk Gruszecki, Erwin Kessels, Bart Macco,* Eindhoven University of Technology, The Netherlands

As the semiconductor industry is advancing towards the Ångstrom era of transistor scaling, the ultrathin 2D transition metal dichalcogenides (TMDs) serve as potential candidates in replacing the current Si-based channel material for next-generation field-effect transistors (FETs) in integrated circuits (ICs). Atomic layer deposition (ALD) holds great promise as a deposition technique to grow 2D materials directly on the device (i.e. transfer-less) with good conformality in 3D structures and back-end-of-line (BEOL) compatible temperatures. However, several challenges remain in attaining high-quality, large crystals of semiconducting 2D TMDCs like MoS_2, WS_2, and WSe_2 in comparison to other techniques such as chemical vapor deposition (CVD). In addition to that, the development of doping strategies is of great interest to control their conductivity type.

In this presentation, we showcase advanced ALD approaches to address these challenges, through the use of plasma treatments with controlled ion energies, supercycles for incorporating dopants, and surface pretreatments to control the nucleation. We showcase that the morphology and electrical characteristics of ALD WS_2 can be improved upon using an Ar plasma treatment (ICP, RF: 13.56 MHz) in an ABC-type PEALD process along with varying the plasma process parameters such as the exposure time t_p(ranging from 0 to 180 s) and ion energy E_i (from 16 to 41 eV). Sulfur vacancy formation V_s within the film likely induces *p*-type conductivity and enhancement of Hall effect properties with the mobility $\mu_H$ranging between 0.1 and 1.1 $cm^2/(V·s)$ and a carrier density $p$in the order of 10^{19} - 10^{20} cm^{-3} (See Supplementary Information). In the case for MoS_2, substitutional transition metal doping by tantalum (Ta) utilizing a supercycle method, leads to MoS_2 with a similar carrier type and $\mu_H$ranging from 0.04 to 0.16 $cm^2/(V·s)$ and with carrier density p values around ~10^{21} cm^{-3} upon tuning the cycle ratio n MoS_2 : m TaS_2. These results demonstrates a facile method to create degenerate TMDs by PEALD, interesting for potential applications in areas including contact engineering to enhance device performance. Further customizing and refining the design of the ABC process offers a wide range to tune the electrical properties, optimizing them and achieve desired target values.

5:00pm **NS-TuA-15 Deposition and Characterization of Transition Metal Oxide/2d Transition Metal Dichalcogenide Quantum Wells***, **Shih-Hao Tseng**, Yu-Chuan Lin,* Department of Materials Science and Engineering, National Yang Ming Chiao Tung University, Hsinchu, Taiwan

Quantum well heterostructures made of oxide dielectrics and 2D semiconductors provide exciting optoelectronic applications. As this heterostructure is emerging, it is necessary to combine different vapor phase techniques to integrate them in a bottom-up fashion and find ways to characterize them rapidly and non-invasively. We utilize atomic layer deposition (ALD) to deposit aluminum oxide (AlO_x) on a large area 2D WS_2 film grown by metalorganic chemical vapor deposition (MOCVD) to fabricate quantum well superlattices and explore a variety of characterization techniques to study their structures and properties. First, we tested a range of ALD temperature for effective nucleation and growth of continuous 5 and 10 nm AlO_x on WS_2 inert surface. Subsequently, we grow another 2D WS_2 film on top of the 1st stack of AlO_x/WS_2 by MOCVD at low temperatures and encapsulate it with another ALD AlO_x. The single and double AlO_x/WS_2 quantum wells were characterized with Raman and photoluminescence spectroscopy and scanning probe microscopy to understand their optical properties. Next, we used hard X-ray photoelectron spectroscopy (HXPES) to analyze the WS_2 layers sandwiched between AlO_x with varied thicknesses (5-20 nm). To obtain the thickness, roughness, and density of the AlO_x and WS_2 in the quantum wells, X-ray reflectivity (XRR) measurement was performed on the quantum wells. Finally, we examined the impact of AlO_x thicknesses on the effectiveness of HXPES and XRR and the optical and electrical properties of the AlO_x/WS_2 quantum wells.

5:15pm **NS-TuA-16 Engineering Al_2O_3 Interlayer via Atomic Layer Deposition for Enhancing Contact Properties of MoS_2-Based FET***, **Minu Cho**, Hwi Yoon, Sanghun Lee, Seongyeong Park, Inkyu Sohn, Hyungjun Kim,* Yonsei University, Korea

As transistors have advanced and continued to downscale, 2D transition metal dichalcogenides (TMDCs) have gained attention as a promising channel material. However, high contact resistance(R_c) has emerged as a major issue in 2D TMDC field-effect transistors (FETs). This problem is primarily caused by Fermi level pinning, which hinders control over the

Schottky barrier height, even when the metal's work function (WF) is altered, leading to increased contact resistance. Various approaches have been explored to address this issue, among them placing an insulating layer between the metal and the channelhas been proposed as a potential solution to mitigate Fermi level pinning. However, a key challenge in implementing this method is achieving optimal thickness for insulating layer and ensuring uniform deposition of the insulating interlayer on the inert surface of the 2D material.

In this study, we aimed to suppress Fermi level pinning by depositing Al_2O_3 via atomic layer deposition (ALD) as an interlayer for the metal-insulator-semiconductor (MIS) contact of bottom-gated MoS_2 FETs. ALD was utilized to optimize the thickness, leveraging its precise thickness control, and to enhance the uniformity of the Al_2O_3 interlayer on the inert MoS_2 surface. We optimized the coverage of ALD-grown Al_2O_3 by controlling precursor injection pressures on MoS_2 and discovered that improved film uniformity significantly reduces R_c. Additionally, tunneling resistance across the MIS contact was lowered through n-type doping of MoS_2, induced by isopropyl alcohol (IPA) used as a mild oxidant in the ALD process. As a result, with the uniform Al_2O_3 interlayer which induces n-type doping effect we were able to reduce contact resistance by more than two orders of magnitude compared to other MoS_2 FETs fabricated in this study.

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