Tutorial
Room Halla Hall - Session TS-SuA
Tutorial Session

Moderators: Heeyeop Chae, Sungkyunkwan University (SKKU), **Han-Bo-Ram Lee**, Incheon National University

1:00pm **TS-SuA-1 ALD for Hydrogen Technology***, Jihwan An,* POSTECH, Republic of Korea **INVITED**

The production and utilization of hydrogen energy have become essential components in the global energy transition to meet the energy demands of future generations. Fuel cells (FCs), which generate electricity from hydrogen, and electrolysis cells (ECs), which decompose steam into storable hydrogen fuel, offer effective solutions for the conversion and storage of renewable energy, with hydrogen serving as an energy carrier. Consequently, they hold great potential for applications in the future energy sector.

Recently, atomic layer deposition (ALD) has presented exciting research opportunities for FCs and ECs due to its unique features, such as conformality and precise thickness and doping controllability. Individual components of FCs/ECs—the electrolyte, electrolyte–electrode interface, and electrode—can be effectively engineered using ALD nanostructures to address the issues raised during operation.

In this tutorial, we will first provide an overview of the operating principles of FCs and ECs, followed by a discussion of the engineering challenges generally associated with electrochemical performance and stability. Recent examples of the application of ALD-processed nanostructures to FCs and ECs are reviewed, and the quantitative relationship between the ALD process, ALD nanostructures, and the performance and stability of FCs and ECs is elucidated.

1:45pm **TS-SuA-4 ALD Process Optimization Using Machine Learning: A Practical Tutorial for Domain Experts***, Pil Sung Jo,* Gauss Labs Inc, Republic of Korea **INVITED**

As the demand for precise process control in Atomic Layer Deposition (ALD) continues to grow, machine learning (ML) has emerged as a powerful tool to optimize processes, improve efficiency, and enhance quality. However, for many professionals in the ALD field, the journey to incorporating ML into their workflows can seem daunting. This tutorial aims to bridge that gap by providing a practical and approachable introduction to ML, tailored specifically for domain experts in ALD.

The session starts with a quick introduction about me, sharing my journey from being a materials scientist and engineer with hands-on experience in semiconductor fabrication to leading a team of data scientists. I'll talk about why I made this career change and how it happened, showing how combining deep knowledge of a field with data science can create new opportunities and drive innovation.

Next, the basics of ML and introduce a ML system will be covered. I'll start by explaining key concepts like the difference between data-driven and physics-based models, regression vs. classification, and supervised vs. unsupervised learning. Then, we'll introduce a ML system (end-to-end ML pipeline) to help participants understand how machine learning works in real-world production settings—not just in experimental setups. This will include the entire process, from collecting and preparing data to training the model, deploying it, and monitoring its performance.

The core of the tutorial focuses on how domain experts can actively contribute to and benefit from ML. By leveraging their deep process knowledge, experts can play critical roles in feature engineering, validating explainabilty of models, and refining use cases. Particularly, the explainability of machine learning models is a crucial aspect since understanding how models make predictions not only helps in identifying potential biases but also ensures that the outputs align with established physical principles and process knowledge. Practical examples include virtual metrology (VM), such as VM-assisted APC, TTTM, and outlier detection. These use cases will demonstrate how ML can address real-world challenges.

Finally, I will introduce our company's ML solution, showcasing its capabilities through a live demonstration. This product is designed with domain experts in mind, making ML tools accessible and impactful for their research and development efforts.

Whether you are new to ML or looking to integrate it into your ALD workflows, this session will equip you with the knowledge and confidence to start your journey in combining domain expertise with machine learning.

2:30pm **TS-SuA-7 ALD-Enabled Synthesis of Metal-Organic Framework Thin Films: Fundamentals to Applications***, Junjie Zhao,* Zhejiang University, China **INVITED**

With flexible reticular chemistry and well-defined pore structures, metal-organic frameworks (MOFs) have been widely explored as potential adsorbents, catalysts, sensors, drug delivery carriers, dielectrics and candidates for many other applications. Shaping MOFs into thin films provides avenues for innovative devices and composite structures. There are three major challenges for synthesizing MOF thin films: (i) common solvothermal conditions are harsh for delicate substrates; (ii) achieving long-range orders and high porosity is challenging for vapor-phase deposition; (iii) these films are brittle and difficult to transfer between substrates for facile integration. This tutorial briefly reviews the recent advances about ALD-enabled synthesis of MOF thin films, including the fundamental interfacial mechanism involved in the nucleation and growth of MOF thin films seeded/tuned by ALD surfaces, conversion routes from ALD oxides to MOFs, and confined reaction-diffusion systems involving a hydrolyzable ALD surface for wrinkled MOF thin films. We will use representative examples to show how MOF thin films are promising for diverse applications. Finally, we will provide an outlook for the remaining challenges in this field.

3:30pm **TS-SuA-11 The Importance of Interconnect Technology of Si Devices and The Extension of ALD Processes***, Hoonjoo Na,* Samsung Electronics, Republic of Korea **INVITED**

As we scale down, the proportion and importance of interconnect have been increasing for performance improvement, power savings, area scaling, and cost reduction. To meet the demands of the product, an atomic layer deposition (ALD) process has been developed to achieve lower resistance and to fill narrow and deep structures, thanks to the improvement of equipment and materials. Because of the reaction mechanism involving reactants, oxides or nitrides have been widely used for stable ALD processes, but pure metal ALD processes have also begun to be used in products over the past decade by controlling byproducts originating from halides or organic precursors. In the first part of this tutorial, the contributions of ALD processes for advanced interconnects will be covered with several examples from the front-end of line (FEOL), middle of line (MOL), to the back-end of line (BEOL). Resistance alone is not the only consideration for FEOL applications; the effects on transistor performance must also be taken into account. For MOL and BEOL, resistance is the most critical parameter, and there are both common and distinct approaches to achieve breakthroughs. In the second part, the limitations and challenges of ALD processes will be discussed, particularly as we move forward into the era of 3D structures. To overcome future issues and risks, it is essential to understand and adopt a more extensive process concept than what was used for legacy products. To enable further scaling down of devices, interconnect ALD processes must evolve along with advances in processing, equipment, and materials.

4:15pm **TS-SuA-14 Atomic Layer Etching: Basics, Chemistries, and New Developments***, Jane P. Chang,* UCLA **INVITED**

This tutorial discusses the basics of atomic layer etching, with an emphasis on the surface reaction chemistry, followed by new developments.It presents current advances in atomic layer etching of function accelerated nanomaterials and related challenges and opportunities.Examples in both thermal and plasma assisted processes are included, addressing etching selectivity and specificity that are needed to fully integrate novel materials in complex architectures in integrated circuits for commercial and defense applications.

5:00pm **TS-SuA-17 The Era of Atomic Scale Processing: When Area-Selective Deposition Meets Atomic Layer Etching***, Silvia Armini,* IMEC, Belgium **INVITED**

For future sub-5 nm technology nodes, as well as for the integration of high aspect ratio 3D structures such as 3D NAND or 3D DRAM memory devices, IC manufacturing will likely involve the use of area-selective atomic layer deposition (AS-ALD), as other conventional approaches, such as deposition and etch back, might not be viable anymore. While AS-ALD processes have been reported for a variety of materials and processes, which will be summarized in this tutorial, most approaches yield a limited selectivity, for example, due to growth initiation at defects or impurities on the non-growth area. Atomic layer etching (ALE) can be combined with AS-ALD as one step or in supercycles of alternate deposition and etching steps, to remove these defects, extending the process selectivity window.

Thermal atomic layer etching (t-ALE) is based on sequential, self-limiting reactions that yield controlled etching at the atomic level. Thermal ALE utilizes gas phase precursors and accomplishes etching without the ion bombardment employed in plasma ALE. Plasma ALE (p-ALE) is an anisotropic etching process because it uses ion bombardment to form and remove the modified layer. Because there are no line-of-sight restrictions, t-ALE yields isotropic etching and it has many applications in atomic scale processing, such as etching three-dimensional structures, surface smoothing or interface preparation and cleaning. When there are nucleation delays in ALD, deposition-etch back methods will be able to prepare ultrathin and conformal films.

A characteristic of ALE which does not have its direct counterpart in the field of AS-ALD, is the use of simultaneous deposition on one material and etching of another material. If compatible with the specific fabrication step, a mirrored approach could be used to obtain high selectivity when the non-growth area is etched, while material is deposited on the growth area. In this respect, it is also believed that ALD and ALE can be combined in more complex schemes to achieve high deposition selectivity and, vice versa, high etch selectivity.

In this tutorial, a review of ASD and ALE applications will be provided with special focus on their mutual synergy.

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