Tutorial

Room Ybor Salons I-IV - Session TS-SuA

Tutorial Session

Moderators: Parag Banerjee, University of Central Florida, **Nathan Marchak**, IBM, **Christophe Vallée**, University of Albany, **Virginia Wheeler**, U.S. Naval Research Laboratory

1:00pm **TS-SuA-1 Connection between Precursor Molecules and ALD/ASD/ALE Processes**, ***Atsushi Sakurai***, ADEKA CORPORATION, Japan **INVITED**

The development of 3D structures is accelerating to overcome the limitations of lateral scaling in semiconductor devices. As for logic devices, for example, the introduction of the complementary field-effect transistors (CFET) is expected for the future scaling of SRAM cell areas and the improvement of device performance. As for memory devices, high aspect ratio (HAR) memory cells, vertical channel transistors and oxide semiconductors could help to realize a 3D memory device. These 3D architectures with advanced materials could outperform the current device performance and power efficiency.

To enable the complicated 3D structures as well those in 2D, ALD (atomic layer deposition) / AS-ALD (area selective atomic layer deposition) and ALE (atomic layer etching) are indispensable to manipulate the target thin films such as metal, metal nitride and metal oxide films. ALD is the technique to deposit atomically thin, smooth, and conformal films by making a chemical bond between a vapor phase precursor and a substrate surface irrespective of its topological complexity. AS-ALD is the kind of ALD process which can selectively deposit a target thin film on a target area of substrate based on surface chemical differentiation. AS-ALD has a lot of benefits including the elimination of etching processes and the reduction of cost. ALE is the technique to atomically etch a surface film by breaking chemical bonds in an isotropic or anisotropic manner followed by the formation of a volatile etch product. Although ALE is sometimes conceptualized as the opposite of ALD in terms of breaking and making chemical bonds, ALE / ALD are not reverse processes.

This tutorial will focus on the connection between precursor molecule design and ALD / AS-ALD and ALE processes. ALD precursors are basically metalorganic, inorganic and organic molecules. In most cases, they need to have a high vapor pressure, reasonable thermal stability, reactivity and high purity for high quality thin film deposition with an appropriate growth rate on a target substrate. The ALD process co-reactant can also be called an ALD precursor. It is not limited to O_2, H_2O, H_2 and NH_3 but may also be an organic molecule. AS-ALD precursors need to have a growth preference between a target growth area (GA) and non-growth area (NGA). In most cases of AS-ALD, we need an additional molecule such as a SAM (self-assembled monolayer) or SMI (small molecule inhibitor) to support the selective properties of the ALD precursor. ALE precursors are organic, inorganic, metalorganic molecules or their combinations. At the basic level, the ALE precursor, also called an etchant, needs to atomically react with a substrate surface to form a volatile by-product and to etch the surface monolayer.

In this tutorial, we will present and discuss how to design and select ALD / AS-ALD and ALE precursors with real life examples to help the audience deepen their understanding of precursor/thin film process relationships.

1:45pm **TS-SuA-4 Current and Future Perspectives on Atomic Layer Deposition**, ***W.M.M. (Erwin) Kessels***, Eindhoven University of Technology, Netherlands **INVITED**

Atomic layer deposition (ALD) has become one of the most influential thin-film deposition techniques of the past decades, enabling the synthesis of materials with atomic-scale control. By relying on self-limiting surface reactions, ALD offers precise thickness control, excellent uniformity and conformality on complex structures, and access to a wide range of materials. These capabilities have established ALD as a powerful platform for nanoscale materials engineering and an enabling technology across many areas of technology.

This tutorial will briefly revisit the fundamental principles of ALD. Particular attention will be given to the practical aspects of developing ALD processes, including a structured approach with practical steps that can be followed when designing and establishing ALD chemistries. The role of emerging data-driven approaches - including the potential use of AI to support process design and optimization - will also be addressed. As the field matures, the growing body of experimental ALD data is opening new opportunities for more systematic and data-driven approaches to materials discovery.

Building on this foundation, the tutorial will provide a perspective on the current state and future opportunities of ALD as a platform for materials synthesis. While the number of reported ALD processes continues to grow, many technologically relevant materials remain challenging to realize. These challenges include the deposition of new material systems such as 2D materials, the control of film properties at extremely small thicknesses, and the synthesis of ultrathin crystalline materials with well-defined properties.

The tutorial will also place ALD in the broader context of atomic-scale processing, highlighting its complementarity with related approaches such as atomic layer etching (ALE) and area-selective deposition (ASD). Together, these perspectives illustrate how ALD continues to expand its role as a key platform for engineering materials with atomic-level precision.

2:30pm **TS-SuA-7 Current and Future Perspectives on Atomic Layer Etching**, ***Thomas Tillocher***, GREMI - Orleans University - CNRS, France **INVITED**

Atomic Layer Etching (ALE) has been extensively studied these last years for microelectronic processes where high precision is required. ALE is a sequential process based on the self-limiting adsorption of reactive radicals on the first monolayer(s) of the material to be etched (“modification step”). Then, the modified layer is removed selectively to the pristine material under a low energy ion bombardment (“removal step”). This step is also self-limiting, as it stops when the modified layer is cleared, and since the ion energy is set just below the sputtering threshold of the pristine layer. By repeating the cycle, the material is etched one (or a few) monolayer(s) by one (or a few) monolayer(s). Plasma ALE is usually performed in standard ICP etching tools equipped with a gas injection system using fast ALD valves, designed to switch quickly from one gas to another.

For dielectric materials such as SiO_2 and Si_3N_4, ALE is usually achieved at room temperature of the substrate, and the modification step involves a C_4F_8 plasma. Sequential etching has been demonstrated but, this also leads to fluorocarbon deposition on the reactor walls, and eventually to process drifts, which affects reproducibility. Consequently, periodic chamber cleaning is necessary. Cryogenic ALE (Cryo-ALE) has been developed to address this limitation as well as to reduce material damage.

Plasma cryogenic etching consists in cooling the substrate to a temperature generally below -90°C, which significantly increases the surface residence time of adsorbed species. This enhances mechanisms such as passivation, physisorption, condensation or contributes to reduce plasma-induced damage as well chamber wall contamination. Therefore, Cryo-ALE is an ALE process operated at cryogenic temperature of the substrate. Two approaches have been developed and studied for SiO_2, Si and/or Si_3N_4: one where the modification is based on physisorption and the other is based on selective deposition.

This tutorial will first present the basics and the current status of ALE, as well as examples of applications. Next, as a perspective, the interest of cryogenic etching will be discussed.In particular, both physisorption and deposition-based Cryo-ALE processes will be presented: their principle, how they can be implemented and typical results will be described.

3:30pm **TS-SuA-11 Current and Future Perspectives of Area-Selective Deposition**, ***Han-Bo-Ram Lee***, Incheon National University, Republic of Korea **INVITED**

The technological evolution of the silicon industry is shifting from a design-driven era to a nanofabrication-driven era as physical limitations in nanofabrication become increasingly severe in the few-nanometer regime. At the same time, market demand continues to grow rapidly, driven not only by traditional computing and smartphone applications but also by emerging fields such as artificial intelligence and electric vehicles. Consequently, the role of semiconductor foundries, supported by new technological enablers, is becoming more critical than ever.

Area-selective deposition (ASD), based on atomic layer deposition (ALD), has attracted significant attention because it enables bottom-up patterning in three-dimensional structures without the complex etching and lithography processes required in conventional nanofabrication. While ASD has been highlighted for specific applications, such as mitigating edge placement error (EPE), it also holds significant potential for a wide range of semiconductor device applications. However, the practical implementation of ASD is strongly dependent on company-specific device architectures and process schemes, and therefore detailed information has not been widely shared within the research community.

Given the high level of complexity involved in semiconductor device fabrication, broader discussion and idea exchange within the research community could further accelerate technological development. In this tutorial, the fundamental principles of ASD, including the kinetics of nucleation and film growth as well as theoretical interpretations, will be introduced. This will be followed by case studies demonstrating the application of ASD in semiconductor devices. Several examples covering different device structures—such as logic, DRAM, and NAND—will be discussed to illustrate where and how ASD can be effectively utilized in production-level semiconductor device manufacturing.

4:15pm **TS-SuA-14 Atomic Layer Deposition from Lab-to-Fab*, Paul Poodt,*** SparkNano and Eindhoven University of Technology, Netherlands **INVITED**

Atomic Layer Deposition (ALD) has matured from a laboratory technique into a key enabling technology for industrial manufacturing across a broad range of applications. While new and diverse use cases for ALD continue to emerge, translating its inherent advantages (atomic-scale control, conformality, and uniformity) into cost-effective, high-throughput production remains a complex and strongly application-dependent challenge.

This tutorial addresses the industrialization and up-scaling of ALD, focusing on the practical trade-offs that govern throughput, cost of ownership, and precursor utilization. Different reactor concepts, process strategies, and integration approaches are examined to demonstrate why no universal solution exists for scalable ALD. Instead, successful implementation requires careful alignment of process design, equipment architecture, and manufacturing constraints with the specific requirements of each application.

Building on these lessons, the tutorial looks ahead to emerging challenges and opportunities associated with new ALD use cases. Topics include low-footprint processes, advanced process control for porous and high-surface-area substrates, extreme high-volume ALD for mass manufacturing, and the importance of precursor efficiency and large-scale precursor supply. The role of advanced modelling and predictive tools (including artificial intelligence and machine learning) combined with advanced metrology will be discussed. These capabilities are expected to play a critical role in how future ALD processes are developed, optimized, and deployed.

Most new ALD applications have humble beginnings though, often in a laboratory, in the hands of a student. The tutorial will conclude by illustrating how, even at this early stage, thoughtful process and materials choices can lay the foundation for scalable, sustainable, and economically viable future ALD applications.

5:00pm **TS-SuA-17 Advances in Spectroscopic Ellipsometry for ALD and ALE Thin Film Characterization*, Jeremy Van Derslice,*** J. A. Woollam Co., Inc.*; Greg Pribal, **James Hilfiker,*** J.A. Woollam Co., Inc. **INVITED**

Ellipsometry is a non-destructive optical technique that measures changes in the polarization state of light upon reflection from a surface, enabling determination of thin-film thickness and optical properties. Ellipsometry is sensitive to angstrom-level changes in film thickness and is therefore well suited to ALD and ALE, where it is used to monitor the cycle-by-cycle evolution of deposited or etched films and to determine growth or etch rates, identify growth windows, and evaluate film quality. This tutorial will introduce the principles of ellipsometry and show how the technique is conventionally used for ALD/ALE applications, from basic thickness determination to optical modeling of multilayer process stacks. We will then highlight three current topics relevant to the ALD/ALE community. First, we will discuss the use of artificial intelligence and other computational tools for automated model generation and parameter fitting. These tools are designed to reduce the level of expertise needed to interpret ellipsometry data. Second, we will examine modeling concepts for metallic films whose optical properties, specifically the free carrier parameters, vary as a function of thickness, which creates challenges for data interpretation. Third, we will introduce infrared ellipsometry using our new QCL-based IR-VASE platform, which enables high-speed IR measurements that provide insights into the chemistry involved in deposition and etch processes. By combining fundamentals with emerging methods, this tutorial will provide practical guidance for using ellipsometry in next-generation ALD/ALE applications.

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