

## Area Selective ALD

### Room Hall 3E - Session AS-MoA

#### Selective ALD by Area-Deactivation

Moderator: Stacey Bent, Stanford University

4:00pm **AS-MoA-11 Revealing New AS-ALD Chemistries with Ab Initio Approaches: From Interpretation to Prediction**, Ralf Tonner-Zech, Leipzig University, Germany

INVITED

Area-selectivity is currently one of the key challenges in atomic layer deposition. The selectivity observed stems from different surface reactivities of precursors and - for inhibitor-based approaches - the inhibitor molecules. Ab initio approaches like density functional theory can help to reveal the key mechanisms underlying this selectivity. They thus help to understand experimental findings in the first step (interpretation). In the second step, theory can ideally provide design principles for inhibitors and precursors from detailed analysis of several systems (prediction). I will present our progress in both areas: (i) interpretation of new AS-ALD reactivities for small molecule inhibitor-(SMI)-based approaches to ALD on dielectric and metallic surfaces,[1] and (ii) understanding of design principles for SMIs and precursors using ab initio computations and electronic structure analysis.

[1] J. Yarbrough, F. Pieck, A. B. Shearer, P. Maue, R. Tonner-Zech, S. F. Bent, *Chem. Mater.* 2023, 35, 5963–5974; (b) J. Yarbrough, F. Pieck, D. Grigjanis, I.-K. Oh, P. Maue, R. Tonner-Zech, S. F. Bent, *Chem. Mater.* 2022, 34, 4646–4659; (c) S. Zoha, F. Pieck, B. Gu, R. Tonner-Zech, H.-B.-R. Lee, in revision.

Funding from a Merck KGaA, Darmstadt, Germany 350<sup>th</sup> Anniversary Research Award is gratefully acknowledged.

4:30pm **AS-MoA-13 Area Selective Atomic Layer Deposition Using a Size Cutter**, Han-Bo-Ram (Boram) Lee, Incheon National University, Republic of Korea

INVITED

Area-selective atomic layer deposition (AS-ALD) has received great attentions due to its potentials for a key toolbox in the nanofabrication of Si devices. The approach using inhibitor molecules which locally change surface chemical properties to inert toward the following ALD reactions has been widely used. The defect density of inhibitor layer which is a potential nucleation site should be minimized to achieve high selectivity, however, it is difficult due to the steric hindrance of inhibitor molecule during comparative adsorption. In this presentation, a simple approach to minimize the steric hindrance effects of inhibitor and maximize the blocking property is introduced. The ligand size of inhibitor layer could be reduced by only additional pulse of H<sub>2</sub>O and the adsorption coverage of inhibitor could be increased. The concept of size cutter has been interpreted by using theoretical calculations with density functional theory (DFT) and Monte Carlo (MC) simulation and the results show highly consistency with experimental observation. The results could provide insights for the next generation nanofabrication in the semiconductor technology using AS-ALD.

5:00pm **AS-MoA-15 ALD Young Investigator Award Finalist Talk: ALD Grown Self-Assembled Monolayers: Using Area-Selective Deposition to Characterize Molecular Scale Pinholes**, Sakari Lepikko, R. Ras, Aalto University, Finland

Area selective atomic layer deposition has become a key method for creating patterned thin film structures for various applications in the semiconductor industry. Self-assembled monolayers (SAMs) are often used for de-activating surfaces, to block the ALD film growth (Figure 1). SAMs allow easy patterning, are capable of inhibiting wide variety of precursors, and are suitable on various substrates. Whereas certain SAM chemistries, such as alkyl trichlorosilanes are good for de-activating oxide substrates, they are also notoriously difficult to grow defect free, thereby reducing the SAM effectiveness to block ALD growth.

A promising option is to grow the SAMs directly in the ALD reactor, as it provides dry vacuum environment with good temperature control, thus making it an ideal tool for optimizing the SAM growth. Here, we present how the quality of non-fluorinated octyltrichlorosilane SAMs can be tuned to better block growth of various ALD films with differently sized precursor molecules [1]. By increasing SAM growth time its areal coverage increases, which leads to reduction of pinholes in the SAM and thus to the adsorption sites for the ALD reactant molecules (Figure 2). We also show that the maximal pinhole size reduces with the increasing coverage, which helps blocking adsorption of smaller ALD precursor molecules such as diethyl

zinc. We see that growing SAMs directly in an ALD reactor could provide means to create more uniform SAMs with better resistivity against various ALD precursors, thus helping fabrication of even more demanding nanostructures in the semiconductor field.

We demonstrate that these SAMs have tunable hydrophobicity with extraordinarily low droplet friction. We demonstrate the world's most slippery surface by coating of SAM on black silicon.[1]

Lepikko, S., *et al.* Droplet slipperiness despite surface heterogeneity at molecular scale. *Nature Chemistry* (2024). <https://doi.org/10.1038/s41557-023-01346-3>

5:15pm **AS-MoA-16 Area-Selective Etching of Poly(lactic acid) via Hydrogenolysis for Self-Aligned ALD**, Valteri Lasonen, M. Ritala, University of Helsinki, Finland

Our previous works have demonstrated that area-selective etching (ASE) of polymers is a novel approach for enabling self-aligned ALD.<sup>1,2</sup> In ASE, a polymer film is decomposed only on catalytic surfaces whereas on non-catalytic surfaces the polymer stays intact. ASE was demonstrated in the air using Pt as the catalytic and native SiO<sub>2</sub> as the non-catalytic surface with two polymers, polyimide and poly(methyl methacrylate) (PMMA). After the ASE of polyimide, ALD-Ir grew only on the exposed Pt surface, whereas no growth was observed on the polyimide. In the case of ASE of PMMA, small amount of ALD-Ni growth occurred also on PMMA. However, a simple lift-off after the ALD removed the unwanted Ni. Other catalytic surfaces were also identified, such as CeO<sub>2</sub>. Furthermore, it was demonstrated that only a small amount of ALD-Pt or ALD-CeO<sub>2</sub>, even down to a fraction of a monolayer, was enough to show a clear catalytic effect. This means that small amounts of Pt can be deposited on a metal surface, and CeO<sub>2</sub> on an insulator surface, to catalytically activate them. This is important because neither Pt nor CeO<sub>2</sub> is commonly used in semiconductor devices.

Many materials used in semiconductor devices are prone to oxidation when heated in the air, thus, non-oxidative atmospheres must be found for ASE. Two such atmospheres, inert (99.999% N<sub>2</sub>) and H<sub>2</sub> (5% H<sub>2</sub> in Ar), were tested with PMMA and polyimide.<sup>1,2</sup> Out of all the surfaces tested only Ti, Pd, and Cu showed some catalytic effect in the inert atmosphere and/or in the presence of H<sub>2</sub>. For example, the well-known hydrogenolysis catalyst, Pt, did not show any catalytic effect on the decomposition of PMMA in the presence of H<sub>2</sub>. This is most likely because PMMA is not susceptible to hydrogenolysis, unlike condensation polymers, such as poly(lactic acid) (PLA). Here, we demonstrate that PLA is catalytically decomposed on several known hydrogenolysis catalysts, such as Pt, Ir, and Ni in the presence of H<sub>2</sub> whereas in the inert atmosphere PLA films stay intact on these surfaces at the same temperatures. Additionally, Co is demonstrated to work as a catalytic surface also in the inert atmosphere. In this case the removal mechanism is catalytic cracking of the polymer. These new findings give us confidence that ASE of polymers is possible with plethora of different surface combinations by carefully choosing the right catalytic material, polymer, and atmosphere, thus allowing new self-aligned ALD processes.

#### References

1. Zhang et al. *Coatings*. 2021, 11(9), 1124.
2. Lasonen et al. *Chem. Mater.* 2023, 35(15), 6097–6108.

5:30pm **AS-MoA-17 Selective Surface Fluorination to Enable ASD of Polymer and Metal Oxide on SiN vs. SiO<sub>2</sub>**, Jeremy Thelven, H. Oh, H. Margavio, C. Oldham, G. Parsons, North Carolina State University

3D integration of semiconductor devices such as Gate-All-Around FETs and vertical device stacking is being implemented to reduce power consumption and enable further scaling for logic and memory devices.<sup>1</sup> There is a critical need to reduce the processing budgets to achieve such advanced designs and area-selective deposition (ASD) offers a bottom-up approach to achieve the desired scaling goals.<sup>2</sup> The ability to selectively react and deposit on an oxide vs nitride surface is widely recognized as key roadblock for scaling due to the chemical similarity of these surfaces. ASD on nitride vs oxide surfaces, or vice versa will provide new options for patterning, to improve self-alignment, and to reduce edge placement errors. In this work, we demonstrate the use of a selective surface fluorination treatment to promote ASD on SiN vs. SiO<sub>2</sub>.

To demonstrate ASD on SiN vs. SiO<sub>2</sub>, we explored a surface treatment using molybdenum hexafluoride (MoF<sub>6</sub>) on blanket SiN and SiO<sub>2</sub> wafers. Next, we deposited about 50nm of polypyrrole (PPy) CVD on both surfaces. We found that PPy proceeded to grow as a film on the SiN surface after a brief nucleation delay, while only showing isolated nuclei on the fluorinated SiO<sub>2</sub> surface. As a further demonstration, experiments were performed on

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patterned SiO<sub>2</sub>/SiN wafers which further confirmed PPy selective growth. We believe the MoF<sub>6</sub> exposure leads to the fluorination of both surfaces, which was confirmed by XPS, where this fluorination selectively passivates PPy growth on the SiO<sub>2</sub> surface. To extend this demonstration of ASD on SiN vs SiO<sub>2</sub> to other types of materials, we recently tested the treatment with the deposition of TiO<sub>2</sub> through ALD. We found that this selective fluorination passivation of the SiO<sub>2</sub> surface allows for selective growth of TiO<sub>2</sub> on SiN. The mechanisms behind selectivity, and the extent of passivation are currently under investigation by our group.

1 Datta, S.; Dutta, S.; Grisafe, B.; Smith, J.; Srinivasa, S.; Ye, H. Back-End-of-Line Compatible Transistors for Monolithic 3-D Integration. *IEEE Micro* 2019, 39 (6), 8–15. <https://doi.org/10.1109/MM.2019.2942978>.

2 Decadal Plan for Semiconductors. Semiconductor Research Corporation. <https://www.src.org/about/decadal-plan/>

## Area Selective ALD

### Room Hall 3E - Session AS-TuM

#### Selective ALD

**Moderators:** Han-Bo-Ram Lee, Incheon National University, Angel Yanguas-Gil, Argonne National Lab

10:45am **AS-TuM-12 A Novel SMI for AS-ALD, Molly Alderman, A. Upadhyay**, Carleton University, Canada; **M. Griffiths, K. Blakeney, D. Agnew, P. Lemaire, J. Smith, D. Hausmann**, LAM Research; **S. Barry**, Carleton University, Canada; **D. Mandia**, LAM Research

Area selective atomic layer deposition (AS-ALD) presents a means to achieve the ever-increasing architectural density and decrementing feature sizes demanded by Moore's law beyond what is possible when patterning by photolithography alone. With inherently selective ALD processes being rare, the use of surfactants to promote or inhibit growth of films has gained traction.<sup>1</sup> In particular, small molecule inhibitors (SMIs) are preferable to self-assembled monolayers (SAMs) for modification of growth behaviour owing to their smaller size, improved thermal characteristics, vapour phase adsorption, and (when compared to the most common SAMs) lack of heavy heteroatoms, in particular sulfur, preventing film contamination.<sup>2</sup>

We have synthesized a family of novel polyfluorinated isonitriles with different chain lengths for use as a SMI in AS-ALD. As an example, Long Chain Inhibitor is readily synthesized in two steps from the amine and is volatile, with a 1 Torr vapour pressure at 33 °C. This compound shows promising selectivity for adsorption to metals over oxides as measured via quartz crystal microbalance (QCM), saturating gold with a surface density of 62 ng/cm<sup>2</sup> (0.81 molecules/nm<sup>2</sup>) with concurrently negligible adsorption on alumina (Figure 1). The synthesis and thermal characterization of several fluorinated isonitriles will be discussed. Their selectivity for metal surfaces by QCM, as well as ToF-SIMS mapping on metal/SiO<sub>2</sub> patterned substrates will be shown to demonstrate selectivity, with excellent resolution provided by the high fluorine content of the molecule. Selective inhibition of zinc oxide ALD will also be discussed and selectivity values will be reported.

#### References

(1) Parsons, G. N.; Clark, R. D. Area-Selective Deposition: Fundamentals, Applications, and Future Outlook. *Chem. Mater.* **2020**, *32* (12), 4920–4953. <https://doi.org/10.1021/acs.chemmater.0c00722>.

(2) Yasmeen, S.; Ryu, S. W.; Lee, S.-H.; Lee, H.-B.-R. Atomic Layer Deposition Beyond Thin Film Deposition Technology. *Advanced Materials Technologies* **2023**, *8* (20), 2200876. <https://doi.org/10.1002/admt.202200876>.

11:00am **AS-TuM-13 Atomic Layer Plasma Treatment for Area-Selective Atomic Layer Deposition of High-Quality SiO<sub>2</sub> Thin Film, Sanghun Lee, S. Seo, T. Kim, H. Yoon, S. Park, S. Na, J. Seo**, Yonsei University, Republic of Korea; **W. Noh**, Air Liquide, Republic of Korea; **S. Chung, H. Kim**, Yonsei University, Republic of Korea

Area-selective atomic layer deposition (AS-ALD) has been intensively studied due to its demonstrated versatility in recent nanotechnology applications. The priority focus in AS-ALD is achieving the desired selectivity; thus, most studies to date have concentrated on the reaction mechanism of ALD on the growth/non-growth substrate or sought novel methodologies to resolve challenges in its implementation in high-volume manufacturing. On the other hand, the qualities of film deposited by AS-ALD were usually not highlighted. In this work, we studied the AS-ALD approaches that could enhance the selectivity and film quality simultaneously. We developed AS-ALD SiO<sub>2</sub> on SiO<sub>2</sub> whereas SiO<sub>2</sub> was not grown on SiN<sub>x</sub>. NH<sub>3</sub> plasma pre-treatment was employed to functionalize SiN<sub>x</sub> surface with more –NH species which are known for their lower reactivity toward Si precursors. The results show that NH<sub>3</sub> plasma pre-treatment is effective in increasing selectivity, but the plasma condition needs to be controlled to avoid inducing damage to the SiN<sub>x</sub> surface, which could offer reactive sites for precursor adsorption. We carried out ALD supercycle of NH<sub>3</sub> plasma pre-treatment and ALD SiO<sub>2</sub> to achieve higher selectivity. When the number of NH<sub>3</sub> pre-plasma treatment cycles was increased, the growth of SiO<sub>2</sub> on SiN<sub>x</sub> was further delayed. Furthermore, layer-by-layer NH<sub>3</sub> plasma pre-treatment densified the SiO<sub>2</sub> film owing to ion bombardment, as revealed in etching characteristics and x-ray reflection spectra. Moreover, NH<sub>3</sub> plasma pre-treatment did not result in incorporation of nitrogen into growing SiO<sub>2</sub> film as analyzed by x-ray photoelectron spectroscopy. Consequently, atomic layer NH<sub>3</sub> plasma pre-

treatment enabled a higher selectivity and improved SiO<sub>2</sub> film quality, as evaluated by the electrical property measurement of metal-oxide-semiconductor capacitor.

11:15am **AS-TuM-14 Enhancing Selectivity for AS-ALD of MoO<sub>2</sub> through Hydrogen Treatment: Strategy of Surface Cleaning and Expanding Deactivated Areas, Hae Lin Yang, J. Kwon, C. Park**, Hanyang University, Korea; **S. Lee, B. Kim, C. Jung, H. Lim**, Samsung Electronics Co., Inc., Republic of Korea; **J. Park**, Hanyang University, Korea

Recently, in the field of DRAM capacitors, the demands for precisely depositing MoO<sub>2</sub> thin films for resolving the high leakage issue between high-k dielectric and TiN electrodes, onto TiN without additional patterning<sup>1</sup>. To meet these demands, Area selective atomic layer deposition (AS-ALD), which allows selective deposition on certain areas without undesired deposition on adjacent areas, is essential. Also accomplish the high selectivity of high-resolution films with high spatial resolution, the introduction of inhibitors is needed especially small molecular inhibitors (SMIs). SMIs consist of inert tail portions composed of single molecules, enabling them to have small sizes suitable for narrow lines at the nanometer scale. However, SMIs typically have short tail groups that cannot undergo van der Waals interactions, and they cannot densely cover the substrate surface due to steric hindrance from adjacent adsorbed SMIs during precursor adsorption<sup>2</sup>. Therefore, considerations regarding the treatment of unadsorbed areas and the removal of remaining reactive groups after SMI adsorption are necessary. To address this, we added a hydrogen treatment process during the AS-ALD process of MoO<sub>2</sub> using TCPS [C<sub>6</sub>H<sub>5</sub>SiCl<sub>3</sub>] and DMA-TMS [(CH<sub>3</sub>)<sub>3</sub>Si(CH<sub>3</sub>)<sub>2</sub>] as SMIs and analyzed the effects of hydrogen treatment on surface properties and selectivity using XPS, WCA, and AES mapping. Additionally, we calculated reaction energies for each adsorption step and final forms for each SMI-adhered surface using DFT and RSA simulations. TCPS, owing to its aromatic phenyl ring, covers a wider range of SiO<sub>2</sub> surfaces than DMA-TMS. However, only two out of three Cl ligands react, leaving about 1.4% of the remaining Cl ligands after TCPS adsorption, increasing the surface energy and acting as adsorption sites for Mo precursors. However, by adding a hydrogen treatment cycle during the process, all remaining Cl ligands were removed, resulting in a 13° increase in WCA and a dramatic increase in selectivity from 61% to 96%. Furthermore, hydrogen treatment not only removed residual impurities but also reduced exposed –OH groups on the surface by converting them to –H, as confirmed by the results of hydrogen treatment added during the DMA-TMS process. Despite the absence of impurities to be removed, the WCA increased by approximately 7° after hydrogen treatment, and the selectivity also increased from 84% to 94.5%. In this way, appropriate treatments during AS-ALD processes, though simple, can effectively increase selectivity, enabling precise selective deposition in desired areas even in complex structures.

11:30am **AS-TuM-15 Contra-Selective Deposition of SiO<sub>2</sub> on Metals, Chad Brick, T. Ogata**, Gelest, Inc

In recent years, an increasing number of area selective processes have been developed for the deposition of dielectric films on dielectric layers. However, reports of the selective deposition of dielectric films on metal regions of a substrate are comparatively rare, typically involving the deposition of high-k dielectric films with significantly different chemistry with respect to the target low-k non-growth areas such as SiO<sub>2</sub> or SiN. In this study, a series of heteroatom-containing silanes with inherent selectivity towards metals over SiO<sub>2</sub> and SiN and their conversion to SiO<sub>2</sub> via plasma-enhanced atomic layer deposition have been investigated. It will be shown that under appropriate conditions, indefinitely thick films of SiO<sub>2</sub> can be selectively grown on metals such as copper and cobalt with pre-existing native or thermal silicon dioxide as the non-growth substrate. Mechanisms of this unusual “contra-selectivity”, with a film growing not only on a material other than itself with its unblocked self as a non-growth surface, but also continuing to grow to arbitrary thickness despite the near-identical nature of the growth and non-growth surfaces after the first few deposition cycles, will be discussed.

11:45am **AS-TuM-16 Photoluminescent Graphene-Lanthanide Heterostructures via Direct Laser Writing and Area-Selective Atomic-Molecular Layer Deposition, Aleksei Emelianov, K. Mentel**, University of Jyväskylä, Finland; **A. Ghazy**, Aalto University, Finland; **A. Johansson**, University of Jyväskylä, Finland; **M. Karppinen**, Aalto University, Finland; **M. Pettersson**, University of Jyväskylä, Finland

Area-selective atomic-molecular layer deposition (AS-ALD/MLD) is a promising “bottom-up” alternative to the current nanopatterning techniques [1,2]. It has been used on a variety of materials, including the

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growth of two-dimensional materials (2DM). While there are examples of AS-ALD being used on 2DM, the approach of combining it with AS-MLD is still mostly unexplored. Due to the inherent 2D nature, the surface of 2DM does not provide sufficient reactive sites for the chemisorption of ALD/MLD precursors compared with traditional microelectronics. Functionalization of certain surface areas is required to provide the selective growth of materials. Recently, we have overcome the chemical inertness of graphene to ALD precursors by local activation using direct femtosecond laser two-photon oxidation (TPO) [3] for selective ZnO deposition [4].

In this study, we guided the growth of Eu-organic thin films on top of single-layer graphene via TPO. We achieved high homogeneity and more than 90% selectivity in locally activated predefined regions for Eu films up to 15 nm. The polymer used for graphene transfer significantly affects the selectivity of the ALD/MLD process, as it might leave residues and promote unnecessary deposition in pristine graphene areas. The fabricated graphene/Eu-organic thin films exhibited high photoluminescence at 615 nm even when excited with a 532 nm laser. The films are suitable for various applications in optoelectronics, sensors, and LEDs.

References:

[1] G. N. Parsons, R. D. Clark, *Chemistry of Materials*, 32, 4920 (2020).

[2] J. Multia, M. Karppinen, *Advanced Materials Interfaces*, 9, 2200210 (2022).

[3] J. Aumanen, A. Johansson, J. Koivistoinen, P. Myllyperkiö, M. Pettersson, *Nanoscale*, 7, 2851 (2015).

[4] K. K. Mentel, A. V. Emelianov, A. Philip, A. Johansson, M. Karppinen, M. Pettersson, *Advanced Materials Interfaces*, 9, 2201110 (2022).

## Area Selective ALD

### Room Hall 3 - Session AS-TuP

#### Area Selective ALD Poster Session

##### AS-TuP-1 Selective Metal Blocking using Vapor-Phase Self-Assembled Monolayers for Area-Selective Atomic Layer Deposition of Dielectrics, *Jeong-Min Lee, W. Kim*, Hanyang University, Republic of Korea

Area-selective atomic layer deposition (AS-ALD) offers complementary bottom-up patterning with atomic-level accuracy on pre-defined areas in conjunction with conventional top-down patterning, so it has attracted tremendous interest for enablement of multi-dimensional nanostructures toward sub-10 nm scale technology. In this study, we report a methodology for achieving selective deposition of dielectric thin films by using vapor-phase self-assembled monolayers (SAMs) accompanied by post-surface treatment. First, we investigated the AS-ALD of  $ZrO_2$  films for dielectric versus metal selectivity through vapor-phase phosphonic acid (PA) SAMs treatment with long alkyl chains. The blocking capability of PA SAMs was comparatively evaluated with  $O_3$  and  $O_2$  reactants on  $SiO_2$ , TiN, and W substrates, and we confirmed that a relatively high deposition selectivity above 0.9 can be achieved even after ALD 200 cycles with mild oxidizing reactant. Further, electrical properties of  $ZrO_2$  films deposited with both reactants were also investigated comparatively with and without post-surface treatment, and as a result, it was demonstrated that high-quality  $ZrO_2$  films with high dielectric constant can be fabricated through the post-surface treatment. Second, we confirmed the AS-ALD of  $SiO_2$  films only on  $SiO_2$  substrates through vapor-phase functionalization of PA SAMs with fluoroalkyl chains. By using the mild oxidant in subsequent ALD process, selective deposition of  $SiO_2$  thin films over  $\sim 8$  nm on  $SiO_2$  versus TiN and W substrates was successfully demonstrated. We anticipate that this work provides a new strategy to achieve highly selective deposition for AS-ALD of dielectric on dielectric (DoD) application toward the upcoming bottom-up 3D nanofabrication.

##### AS-TuP-2 Area-Selective ALD of Transparent Conductive Oxides by Using Polymer Patterns Generated with High-Precision Capillary Printing, *Ludovic Hahn*, CEA-LETI, France; *M. Pascual, A. Guitton, K. Farmand, A. M'Barki*, Hummink, France; *T. Jullien, L. Golanski, C. Guerin, V. Jousseau*, CEA-LETI, France

Transparent conductive oxide thin films are widely developed for numerous applications in optoelectronics due to their unique properties. However, the oxide film needs to undergo patterning, which is often difficult to achieve with standard lithographic steps. Indeed, those materials are difficult to integrate due to their sensitivity to chemistry, like ZnO, which is water-sensitive. This problem becomes even more dominant when reducing the features for further application. An alternative to photolithographic steps is Area Selective Deposition (ASD), which uses an inhibiting layer such as a polymeric film that prevents oxide deposition on certain controlled regions.

In this work, polymeric films were printed by an innovative direct nanoprinting technique [1]. This High Precision Capillary Printing (HPCAP) technique is based on AFM technologies. A nanopipette filled with the ink of interest will oscillate at a high frequency and deposit the ink to form complex geometries at the surface of a substrate. A precision of 20 nm in the xy plane and a resolution between 100 nm and tens of microns can be achieved, which, coupled with a high deposition rate, makes it a good alternative for additive manufacturing.

Micrometric patterns of polymers, comprising poly(methyl methacrylate) (PMMA), poly(vinyl pyrrolidone) (PVP) and an epoxy-based resist (SU-8) were drawn on silicon substrate. Then TCO, such as ZnO and  $SnO_2$ , were deposited on the patterned polymers by low-temperature ALD. By using spectroscopic ellipsometry, atomic force microscopy, scanning electron microscopy, and energy-dispersive X-ray spectroscopy, it is shown that PMMA inhibits both oxides, compared to PVP and SU-8, which only suppress ZnO growth. Moreover, an exclusion zone around the polymer pattern where oxides are inhibited is observed, depending on the polymer used. The study of the impact of the pattern size (from a few  $\mu m$  to a few tens of  $\mu m$ ) reveals that this exclusion zone is independent of the geometry but mainly depends on the polymer used and the type of oxide deposited.

Finally, the polymers can be selectively removed leading to a selective deposition of TCO and a 10  $\mu m$  pixel array was successfully produced. This original approach combining the direct nanoprinting of a polymer pattern

with the subsequent ALD deposition of TCO appears to be a promising path for the patterning of a sub-10  $\mu m$  matrix of pixels.

[1] M. Pascual, N. Bigan, A. M'Barki, R. Mental, I. Allegro, U. Lemmer, SPIE Opto 2023, 124330E

##### AS-TuP-3 Photo-Enhanced Selective Area Atomic Layer Deposition, *Paul Butler*, Walter Schottky Institut, Technische Universität München, Germany; *L. Sortino*, Ludwig-Maximilians-University of Munich, Germany; *S. Maier*, Monash University, Australia; *I. Sharp*, Walter Schottky Institut, Technische Universität München, Germany

One of the major challenges that ALD currently faces is the lack of lateral control, which has led to an ongoing interest in selective-area ALD (SA-ALD) techniques that can allow for bottom-up fabrication of micro- and nanostructures. In this respect, photo-enhanced ALD (photo-ALD), in which well-defined photoexcitation is used to activate chemical reactions at certain areas on a surface, holds significant promise for SA-ALD. However, relatively few studies on photo-ALD have been conducted and the spatial resolution of this technique remains limited. Here, we present a novel approach to achieving SA-ALD via *in situ* photoexcitation of the surface. Our experiments demonstrate that optical laser excitation enhances ALD-growth of  $TiO_2$  films on gold substrates, with the deposition rate increasing with laser intensity. To investigate the photo-induced reaction, gold-coated silicon substrates were sequentially exposed to titanium isopropoxide (TTIP) and ozone outside the normal ALD process window, with some substrates exposed to illumination from a 515 nm laser. Using *in situ* spectroscopic ellipsometry to monitor the growth rate of the  $TiO_2$  films during the ALD deposition, we find an illumination-activated growth that can be assigned to enhanced oxidation of the adsorbed precursor. Furthermore, patterned illumination through a shadow mask results in laterally structured growth, as verified by *ex situ* ellipsometry mapping. Ongoing work is now devoted to identifying thermal and electronic contributions to the growth mechanism, as well as coupling the exciting illumination to plasmonic gold nanostructures. Overall, this method of selective-area photo-ALD could later be applicable to bottom-up nanofabrication, with applications ranging from nanoscale optoelectronics to photocatalysis.

##### AS-TuP-4 Area-Selective Atomic Layer Deposition of Bilayer Materials Using Polymethylmethacrylate Thin Films as Blocking Layers, *Aditya Chalis hazar*, N. Poonkottil, C. Detavernier, J. Dendooven, Ghent University, Belgium

Area-selective ALD (AS-ALD) is an interesting subset of ALD where materials are selectively grown on specific areas of the substrate. As an additive bottom-up approach, it has immense potential for reducing the number of steps in nanomanufacturing [1-3].

AS-ALD studies have mostly been limited to single-material deposition. Multi-material AS-ALD poses additional challenges as it requires the ALD process chemistries to be compatible in their temperature windows and chemical selectivity. Realizing multi-material ASD has become an interesting challenge in recent years [2,4]. In particular, selective deposition of multilayers can substantially reduce processing time for the fabrication of nanoscale devices.

In this work, we explore the use of metal dialkylamide precursors with polymethylmethacrylate (PMMA) masking layers to realise multi-material AS-ALD. PMMA is a popular AS-ALD inhibitor layer: it can be patterned using various approaches and can easily be removed using exposure to plasma or dissolution in appropriate solvents [3,5].

Here, ALD of  $SnO_2$  and  $Ta_2O_5$  using their dialkylamide precursors and water at 120 °C was performed on Si and blanket PMMA substrates. Selective deposition of  $SnO_2$  and  $Ta_2O_5$  is obtained on Si with negligible deposition on the PMMA blanket substrate after 100 cycles (Figure 1), which was confirmed by XRR/XRF and XPS measurements.  $SnO_2$  was then deposited on a PMMA patterned wafer and studied using energy dispersive X-ray spectroscopy (EDS), which showed deposition between the PMMA pattern (Figure 2a-c). The films were imaged after plasma treatment, which resulted in a  $SnO_2$  pattern (Figure 2d-f). Extending this concept, we deposited a  $SnO_2$ - $Ta_2O_5$  bilayer using a PMMA masking pattern, followed by mask removal with oxygen plasma (Figure 3). This demonstrates the deposition of a multilayer material using one template material without the need for intermediate processing steps. We believe such a combinatorial approach using metal dialkylamide precursors and PMMA can open new avenues to the deposition of patterned multilayer devices for device manufacturing using AS-ALD.

- [1] *Chemistry of Materials*, 2018, 31, 2-12  
[2] *Chemistry of Materials*, 2023, 35, 4375-4384  
[3] *Advanced Materials Interfaces*, 2023, 10, 2201934  
[4] *ACS Nano*, 2021, 15, 12276-12285  
[5] *Chemistry of Materials*, 2020, 32, 4920-4953

**AS-TuP-5 Density Functional Theory Study on Selective Silylation of SiO<sub>2</sub> Against Cu Using Dimethylaminotrimethylsilane**, *Misoo Kim, K. Khumaini, R. Hidayat, H. Kim, W. Lee*, Sejong University, Republic of Korea

Selective cobalt capping of the copper surface has been introduced to improve the electromigration resistance of copper interconnects. Chemical vapor deposition of cobalt on copper is inherently selective against silicon oxide, and the selectivity can be enhanced by silylation of the oxide surface to form an alkyl-terminated surface. In the previous work, we studied the selective chemisorption of the cobalt precursor on copper and showed that chemisorption is favored on copper but not on silicon oxide. We also showed that physisorption and chemisorption of the cobalt precursor are more difficult on alkyl-terminated SiO<sub>2</sub> than on OH-terminated SiO<sub>2</sub> [1]. Recently, another research group demonstrated that the alkyl-terminated surface is also essential for the selective atomic layer deposition of ruthenium films [2]. They observed that at 250°C, dimethylaminotrimethylsilane (DMATMS) readily reacts with surface -OH groups on SiO<sub>2</sub> to form -O-Si(CH<sub>3</sub>)<sub>3</sub> groups. However, the theoretical study of the reaction mechanism to form an alkyl-terminated silicon dioxide surface is rare. In addition, the reaction of DMATMS with metallic surfaces has not been reported by either experimental or theoretical studies. In the present work, we performed density functional theory (DFT) calculations to study the reaction mechanism for the selective silylation of DMATMS on silicon oxide against copper surfaces. We constructed two substrates, vicinal OH-terminated SiO<sub>2</sub> and bare copper substrate. All possible chemisorption pathways were considered. The reaction and activation energies of chemisorption on these two surfaces were calculated and compared. In addition, the Gibbs free energy changes for silylation were determined to explain the selective silylation at process temperature. The results can provide fundamental insights into the selective surface inhibition mechanism for area-selective deposition.

## Acknowledgments

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**AS-TuP-6 Self-Aligned Patterning of Tantalum Oxide on Cu/SiO<sub>2</sub> with Inherent Selective Atomic Layer Deposition**, *Kun Cao, Z. Qi*, State Key Laboratory of Intelligent Manufacturing Equipment and Technology, School of Mechanical Science and Engineering, Huazhong University of Science and Technology, China; *B. Shan*, State Key Laboratory of Materials Processing and Die & Mould Technology, School of Materials Science and Engineering, Huazhong University of Science and Technology, China; *R. Chen*, State Key Laboratory of Intelligent Manufacturing Equipment and Technology, School of Mechanical Science and Engineering, Huazhong University of Science and Technology, China

The chemical principal and mechanisms that enable selective atomic layer depositions are gaining rapid growing interests, which have unlocked attractive avenues for the development of novel nanostructures by depositing atoms at desired surface locations. In this talk, the inherently selective atomic layer deposition processes will be discussed. Tantalum oxide was studied on a series of oxide substrates. Although the oxides have -OH groups on the surface and proposed to have similar nucleation sites, there are long nucleation delays on basic oxides. The H-transfer reaction is a key factor to influence the reaction barrier. It is hard to nucleate on basic substrates because the H-transfer reaction is blocked. Another demonstration is the redox-coupled inherently selective ALD for self-alignment of tantalum oxide on SiO<sub>2</sub>/Cu nanopatterns. By adding an in-situ ethanol reduction pulse before each traditional binary ALD cycle, and the 'reduction-adsorption-oxidation' ALD process increases the selectivity. Self-aligned manufacturing on nanoscale Cu/SiO<sub>2</sub> patterns without excessive mushroom growth at the edge and undesired nucleation defects on the Cu region. The process can be reliably repeated to yield more than 5 nm-thick Ta<sub>2</sub>O<sub>5</sub> on the SiO<sub>2</sub> region, while no undesired deposition occurs on Cu patterns. In addition, an anisotropic growth model with the dynamical competition of expansion and dissociation of the nucleus is proposed to nucleation delay are quantitatively predicted and the model provides a practical method to evaluate the selectivity of ALD theoretically.

**AS-TuP-8 What Happens to Small Molecule Inhibitors after the Selectivity Is Lost: 4-Fluorophenylboronic Acid Functionalization of Silicon Surface to Inhibit TiO<sub>2</sub> Deposition**, *Andrew Teplyakov, D. Silva-Quinones, J. Mason, R. Norden*, University of Delaware

As the size of the components in electronic devices decreases, new approaches and chemical modification schemes are needed to produce nanometer-size features with bottom-up manufacturing. Organic monolayers can be used as effective resists to block the growth of materials on non-growth substrates in area-selective deposition methods. However, choosing the appropriate surface modification requires knowledge of the corresponding chemistry and also a detailed investigation of the behavior of the functionalized surface in realistic deposition schemes. The 4-fluorophenylboronic acid (FPBA) can be used as a model to investigate the possibility to utilize the Si(100) surface functionalized with this compound as a non-growth substrate in a titanium dioxide (TiO<sub>2</sub>) deposition scheme based on sequential doses of tetrakis(dimethylamido)titanium (TDMAT) and water and to follow what happens at the interface when the selectivity is eventually lost. A combination of X-ray photoelectron spectroscopy (XPS) and time-of-flight secondary ion mass spectrometry (ToF-SIMS) allows for a better understanding of the process. The functionalized surface is shown to be as effective non-growth area to TiO<sub>2</sub> deposition when compared to currently used H-terminated silicon surfaces but to exhibit much higher stability in ambient conditions. Thermal treatment and analysis of F and B labels allow for investigating interface stability and opportunities to use the scheme for monolayer doping.

**AS-TuP-9 Modelling the Reactivity of Small Molecule Inhibitors by Density Functional Theory**, *Fabian Pieck, R. Tonner-Zech*, Wilhelm-Ostwald Institut for Physical and Theoretical Chemistry, Leipzig University, Germany

Within area-selective atomic layer deposition selectivity is achieved by various approaches. We follow the strategy to block growth on the non-growth surface by the deposition of small molecule inhibitors (SMIs) prior to the atomic layer deposition (ALD) process. Here, the selectivity of the process can be improved by understanding the properties and reactivity of the SMIs at an atomic level. Especially, tuning the SMIs with respect to the studied surface and ALD process based on their blocking mechanism is highly valuable. To understand the impact of the SMI structure on its reactivity we are studying two classes of SMIs namely sulfur-based SMIs as diethyl sulfide<sup>1</sup>, dipropyl sulfide and diisopropyl sulfide as well as nitrogen-based SMIs as aniline, pyridine and pyrrole (Figure 1). With SiO<sub>2</sub>, Cu(111) and CuO(111) common metal and oxide surfaces are considered as substrate while these classes of SMIs are experimentally investigated for the deposition of HfO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub>, respectively.

We use ab initio modelling by density functional theory (DFT) to explore adsorption properties and on-surface reactivity of SMIs. Here, adsorption energies are used to find the most stable adsorption structures, while changes in the adsorption energies for multiple adsorbates help to identify ideal inter-molecular spacing and SMI packing density. Reaction paths and transition states are obtained by the nudged elastic band method while obtained activation energies reveal the most likely reactions. In addition, kinetic Monte Carlo (kMC) simulations are used to clarify the impact of obtained intermediates and side reactions on the desired product formation.

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**AS-TuP-12 The Formation of a Bottomless ZnO Barrier Using Inherent ZnO AS-ALD Process for Advanced Metallization**, *Yuki Mori*, TANAKA Precious Metals, Japan; *Y. Son*, Ulsan National Institute of Science and Technology (UNIST), Republic of Korea; *S. Kim*, Ulsan National Institute of Science and Technology (UNIST), Republic of Korea; *S. Kim*, Ulsan National Institute of Science and Technology (UNIST), Republic of Korea

Area selective atomic layer deposition (AS-ALD) is one of the most promising technologies for next-generation interconnect. The bottomless barrier using AS-ALD can reduce interconnect resistance by the deposition of barrier material only on the via sidewall (such as SiO<sub>2</sub>/low-k) not on the via bottom (such as metal). Generally, in the previous studies, barrier materials are selectively deposited using long-chain inhibitors. Therefore, it is difficult to apply it to fine structures. Inhibitor-free inherent AS-ALD is a promising process to solve this problem. ZnO has been reported as the bottomless barrier of Cu interconnects by AS-ALD using an alkanethiol inhibitor [1]. There are many reports regarding AS-ALD of ZnO using inhibitors but the investigation on inherent inhibitor-free AS-ALD of ZnO is very limited [2] thought inhibitor-free ALD has clear advantages with device

scaling-down. In this report, systematic studies on the inherent ZnO AS-ALD with substrate materials and process of substrate materials are described. Here, ALD of ZnO was basically conducted at 120 °C by using diethylzinc (DEZ) and H<sub>2</sub>O as a precursor and a reactant, respectively. DEZ and H<sub>2</sub>O pulsing time were 1 second, where it guarantees the self-limited growth of ZnO. The results shows that there is no incubation cycle on SiO<sub>2</sub>, but ~80 incubation cycle on H-terminated (Si-H). It indicates that the surface OH-groups on SiO<sub>2</sub> promote the adsorption of the Zn precursor, and the surface H-groups on Si-H prevent the adsorption of the Zn precursor. We also investigated about ZnO ALD on different metal surfaces and found that ALD-ZnO process shows a nucleation delay on clean metal surfaces with fewer surface OH-groups. On the easily oxidized metals (such as Ti and Cu), ALD-ZnO process shows almost no incubation cycle. The present findings are expected to enable the formation of bottomless ZnO barrier without providing any inhibitor and reduce interconnect resistance in semiconductor devices.

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## AS-TuP-13 Area-Selective Atomic Layer Deposition by Sputter Yield Amplification on Heavy Elements, Arthur de Jong, M. Bär, M. Merckx, E. Kessels, A. Mackus, Eindhoven University of Technology, Netherlands

Area-selective deposition (ASD) is an emerging approach for device fabrication, that can circumvent the need for lithography for specific layers in a device stack. The selectivity between the growth and the non-growth area is typically achieved on the basis of a chemical difference, by e.g. selective precursor or inhibitor adsorption [1]. To expand the ASD toolbox, a physical approach combining a non-selective ALD process with area-selective sputter etching by ions is investigated in this work. The advantage of sputter etching is its relative independence on temperature and ALD chemistry. To enable selective etching based on sputter yield amplification, the non-growth area requires an element with a much larger mass than the incoming ion [2]. The ions generated by a plasma arrive at the surface with an inwards facing momentum. If an ion collides with an atom having a much larger mass, this momentum is redirected upwards more efficiently as compared to a collision with a light atom. This efficient redirection increases the amount of energy that is transferred to surface atoms, resulting in a larger probability to etch them. The growth area should not contain heavy elements, leading to a much smaller etch rate.

To investigate the selective sputter etching, a thin SiO<sub>2</sub> overlayer deposited by ALD was exposed to low-energy Ar ions. The amount of SiO<sub>2</sub> removed depends significantly on the substrate material underneath (Al<sub>2</sub>O<sub>3</sub>, TiO<sub>2</sub>, Nb<sub>2</sub>O<sub>5</sub>, MoO<sub>3</sub>, HfO<sub>2</sub>, Ta<sub>2</sub>O<sub>5</sub> and WO<sub>3</sub> are investigated here). In general, the heavier the mass of the metal atoms in the substrate, the less SiO<sub>2</sub> is observed after the ion exposure. As demonstration for the feasibility of the approach, SiO<sub>2</sub> was selectively deposited on Al<sub>2</sub>O<sub>3</sub> with respect to a HfO<sub>2</sub> non-growth area. The ASD process consists of repeating supercycles of three SiO<sub>2</sub> ALD cycles and Ar ion exposures from a plasma. Approximately 1.2 nm of selective growth is achieved on the Al<sub>2</sub>O<sub>3</sub>, while most deposition is effectively removed from the HfO<sub>2</sub> (<0.3 nm is observed). It is challenging to maintain the etch selectivity for thicker SiO<sub>2</sub> which can be mitigated by tuning the ALD process. This proof-of-concept shows that exploiting sputter yield amplification can enable ASD processes that are complementary to the existing chemical approaches.

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## AS-TuP-14 Theoretical Investigation on Impurity Formation Mechanism During Area-Selective Atomic Layer Deposition Using Organic Inhibitors, Jiwon Kim, B. Shong, Hongik University, Republic of Korea

Recent advancements in semiconductor devices aim for performance improvement through miniaturization and also employing of three-dimensional architectures. Atomic layer deposition (ALD) is often employed for its advantages of high uniformity and conformality of the deposited thin films. Area-selective ALD (AS-ALD), a potential bottom-up approach for self-aligned fabrication of thin films, may offer process innovations that can solve fabrication challenges. Furthermore, ALD on high aspect ratio (HAR) substrates often involves challenge in conformality. It was recently shown that spatial modulation of the ALD growth rates by adsorption of inhibitors with gradient in density can enhance the conformality within the HAR

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structures. However, in such AS-ALD approaches, molecular inhibitors are often utilized to selectively deactivate the growth of thin films, which may result in increased impurity levels if unwanted side reactions occur. In this study, possible side reactions during AS-ALD of silicon nitride (SiN<sub>x</sub>) using organic small molecule inhibitors (SMIs) are investigated utilizing density functional theory (DFT) calculations. Complete removal of surface passivation group through reaction with the reactants is crucial for the deposition of thin films without carbon impurities. However, nitride materials such as SiN<sub>x</sub> often require high process temperature for thermal ALD, at which decomposition of precursors or inhibitors can occur. Then, the highly reactive chemical species resulting from the thermal decomposition can result in non-selective deposition regardless of surface inhibition. Furthermore, such reaction can result in formation of carbon-containing surface moieties that are significantly stable and resistant against removal, possibly leading to increased amount of carbon impurities. Therefore, our study suggest that the side reactions should be carefully considered for AS-ALD using SMIs.

## AS-TuP-16 Effect of N<sub>2</sub> Co-Flow During Area-Selective Atomic-Layer-Deposition of Al<sub>2</sub>O<sub>3</sub>, Sangjun Lee, Sungkyunkwan University (SKKU), Republic of Korea; C. Park, Y. Choi, S. Jeong, S. Hong, Sungkyunkwan University, Republic of Korea; Y. Cho, H. Lee, H. Kim, A. Klipp, BASF, Republic of Korea; P. Yoo, Sungkyunkwan University, Republic of Korea; H. Kim, Sungkyunkwan University (SKKU), Republic of Korea

In semiconductor device manufacturing, accurate alignment of fine patterns is crucial for optimizing the chip's overall performance. Edge placement error (EPE), which occurs during the via forming process in back-end-of-line metal wiring, leads to increased parasitic capacitance and degrading the reliability and performance of the device [1, 2]. To address this issue, area-selective deposition of dielectric films emerges as a possible solution. This technique selectively elevates the interlayer dielectric or intermetal dielectric between neighboring metal lines, thereby minimizing potential conductive paths and effectively reducing RC delays [3].

In this study, we enhanced the selectivity of Al<sub>2</sub>O<sub>3</sub> atomic layer deposition (ALD) on dodecylphosphonic acid-treated Cu substrates by co-flowing N<sub>2</sub> during Al-precursor (trimethylaluminum) injection. The selectivity significantly increased as the N<sub>2</sub> flow rate was increased from zero to 200 sccm, prompting the utilization of various characterization techniques to determine the origin. Contact angle measurements were taken to compare the blocking capability of the self-assembled monolayer when exposed to both the precursor and N<sub>2</sub>. The selectivity was evaluated by X-ray fluorescence and X-ray photoelectron spectroscopy analyses. Additionally, possible changes in the dielectric constant of the Al<sub>2</sub>O<sub>3</sub> film were examined by electrically characterizing the capacitors fabricated with Al<sub>2</sub>O<sub>3</sub> films deposited using various N<sub>2</sub> co-flow rates.

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