ALD Applications

Room Grand Ballroom A-C - Session AA1-MoA

ALD for Biological and Space Applications

Moderators: Elton Graugnard, Boise State University, Mato Knez, CIC nanoGUNE

1:30pm **AA1-MoA-1 Atomic Layer Deposition on Pharmaceutical Particles for Inhaled Drug Delivery**, ***Damiano La Zara***, Delft University of Technology, Netherlands; *D Zhang, M Quayle, G Petersson, S Folestad,* AstraZeneca, Sweden; *J van Ommen,* Delft University of Technology, Netherlands

Drug delivery by inhalation provides a targeted treatment for respiratory diseases such as asthma and chronic obstructive pulmonary disease. A growing amount of new inhaled active pharmaceutical ingredients (APIs) includes amorphous drugs, which are often very moisture-sensitive, as well as expensive and less potent drugs, which require improved flowability and aerosolization efficiency to meet the drug load requirements and to minimize their cost. Moreover, there is no commercially viable extended-release technique for inhaled drug particles. Therefore, there is an unmet need for novel solutions to provide surface modification of inhaled pharmaceutical powders that lead to improved processability and stabilization of solid state forms (e.g., amorphous, metastable, polymorphs, hydrates) and, most importantly, clinical benefits, e.g., controlled release of API from dosage forms.

In this work, we demonstrate the use of atomic layer deposition (ALD) as a route to modify the properties of inhaled pharmaceutical particles, namely (i) dispersibility, (ii) stability to moisture and (iii) dissolution rate. We deposit ultrathin oxide ceramic films, namely Al_2O_3, TiO_2 and SiO_2, on both API (e.g., budesonide and salbutamol) and excipient (i.e., lactose) particles, both crystalline and amorphous. The ALD process is carried out at ambient conditions in a fluidized bed reactor for a range of cycles from 10 to 50, using TMA/O_3, $TiCl_4$/H_2O and $SiCl_4$/H_2O as precursors for Al_2O_3, TiO_2 and SiO_2 ALD, respectively. The deposition strongly depends on the surface crystal structure of the particles. Time-of-flight secondary ion mass spectrometry and transmission electron microscopy reveal the deposition of uniform and conformal nanofilms on crystal surfaces, whereas uniform but non-conformal nanofilms are observed on amorphous surfaces. The dispersion properties are evaluated both in the liquid and dry state. The ALD-coated particles exhibit considerably higher dispersibility in both water and ethanol solutions, thus suggesting higher bioavailability, than the uncoated ones. In-vitro aerosolization testing by the next generation impactor shows improved fine powder delivery (<5 µm, i.e., particle size range relevant for inhalation) and greatly reduced powder retention in the inhaler for the ALD-coated particles. The dispersion and aerosolization properties are retained even upon different conditions of temperature (25-40 °C) and relative humidity (60-75 %) over 3 weeks. Finally, in-vitro dissolution tests and cell absorption studies reveal more sustained release with increasing film thickness.

1:45pm **AA1-MoA-2 The Use of Atomic Layer Deposition to Increase the Availability of Medical Radio-Isotopes**, ***Ruud van Ommen***, *J Moret, B Wolterbeek, E Pidko, A Denkova,* Delft University of Technology, Netherlands

Since the first use of the radionuclide phosphorus-32 for treatment of haematological patients in the 1930s, the use of radioisotopes in medicine has expanded into a mainstream clinical speciality . It encompasses both diagnostic imaging (exploiting the tissue penetration of gamma rays released in nuclear decay) and targeted therapy (exploiting the cellular toxicity of beta minus and alpha particles) [1]. Radioisotopes are typically applied in single photon emission computed tomography (SPECT, e.g., ^{67}Ga, ^{99m}Tc, ^{111}In, ^{177}Lu) and positron emission tomography (PET, e.g., ^{68}Ga, ^{64}Cu, ^{44}Sc, ^{86}Y, ^{89}Zr), as well as in therapeutic applications (e.g., ^{47}Sc, ^{177}Lu, ^{90}Y, $^{212/213}$Bi, ^{212}Pb, ^{225}Ac, $^{186/188}$Re) [2].

In targeted radionuclide therapy a major hurdle is the dependence on a very limited number of nuclear reactors worldwide to produce these radioisotopes. Especially when some of these reactors are down due to unforeseen maintenance, critical situations for patients relying on the radionuclides can appear.

Atomic layer deposition (ALD) can provide a way to either exploit production in smaller nuclear reactors while still producing radionuclides of high specific activity (i.e. activity per unit of mass) or in some cases to prepare radionuclide generators, that can be placed in hospitals, providing on-site and on-demand supply [3]. In this presentation, we will compare the periodic table for medical radio-isotopes [1] with the periodic table for ALD precursors [4,5]. It will be discussed in which ways ALD can aid in the production of medical radio-isotopes . We will illustrate this by some examples, such as the production of ^{177}Lu and ^{99}Mo.

1. Blower, P. J. (2015). A nuclear chocolate box: the periodic table of nuclear medicine. *Dalton Transactions*, *44*(11), 4819-4844.
2. Price, E. W., & Orvig, C. (2014). Matching chelators to radiometals for radiopharmaceuticals. *Chemical Society Reviews*, *43*(1), 260-290.
3. Moret, J.L.T.M., Wolterbeek, H.T., Denkova, A.G., & van Ommen, J.R., (2016). Thin layer deposition of Lutetium on nano-particles. Presented at 16th International Conference on Atomic Layer Deposition (ALD 2016), Dublin, Ireland, 24–27 July 2016.
4. Puurunen, R. L. (2005). Surface chemistry of atomic layer deposition: A case study for the trimethylaluminum/water process. *Journal of applied physics*, *97*(12), 9.
5. Miikkulainen, V., Leskelä, M., Ritala, M., & Puurunen, R. L. (2013). Crystallinity of inorganic films grown by atomic layer deposition: Overview and general trends. *Journal of Applied Physics*, *113*(2), 2.

2:00pm **AA1-MoA-3 Atomic Layer Deposition for Biosensing Applications**, *O Graniel,* ***Matthieu Weber***, *S Balme, P Miele, M Bechelany,* Institut Européen des Membranes, France

Atomic layer deposition (ALD) is a thin film deposition technique currently used in various nanofabrication processes for microelectronic applications. The ability to coat high-aspect-ratio structures with a wide range of materials, the excellent conformality, and the precise thickness control have made ALD an essential tool for the fabrication of many devices, including biosensors[1].

In this study, we combined ALD, nanosphere lithography (NSL), and electrodeposition to fabricate hollow ZnO urchin-like structures covered by a Au film for surface-enhanced Raman spectroscopy (SERS) applications. The morphology of the structures was investigated using scanning electron microscope (SEM) and transmission electron microscope (TEM). These three dimensional, high-aspect-ratio organized nanostructures enabled the detection of thiophenol with concentrations as low as $1x10^{-10}$ M. The impact of the gold layer thickness, and annealing conditions were investigated. Samples that were not annealed had a better overall reproducibility, whereas the ones annealed presented a stronger enhancement of the Raman signal due to the coalescence of Au into nanoparticles. Lastly, the biosensing capability of the urchin-like ZnO structures was demonstrated by successfully detecting adenine. These proof-of-concepts enabled for a better understanding of the properties of these peculiar nanostructures, and open prospects for the biosensing community.

1. Graniel, O., Weber, M., Balme, S., Miele, P. & Bechelany, M. Atomic layer deposition for biosensing applications. *Biosens. Bioelectron.* **122,** 147–159 (2018).

2:15pm **AA1-MoA-4 Multi-layer Stacked ALD Coating for Hermetic Encapsulation of Implantable Biomedical Microdevices**, ***Joonsoo Jeong***, Pusan National University, Republic of Korea; *S Sigurdsson, F Laiwalla,* Brown University; *R Ritasalo, M Pudas, T McKee, T Pilvi,* Picosun Oy, Finland; *A Nurmikko,* Brown University

Introduction and Main Findings:

Implantable biomedical electronics are a promising technology for medical diagnosis and treatment if they can be made safe for chronic use. There is thus a growing need for compact-volume hermetic packaging methods for miniaturized biomedical implants. Here we describe the use of multi-layer ALD films comprising HfO_2 and SiO_2 (Picosun Oy, Finland) to hermetically encapsulate microscale wireless active electronic implants for use in the brain. The robustness of the 3-D conformal ALD coatings is validated using an accelerated aging test by application of thermal stress (87°C saline) and quantified in terms of water/ionic ingress (leakage currents) as well as overall device performance (the latter via wireless interrogation). ALD coated devices have an extrapolated physiologic temperature lifetime of > 10 years under active electric field stress. Failed devices maintain the layer integrity, and only show gross anomalies on SEM at sample edges likely consistent with handling stresses. This performance is not impacted by opening apertures in the coating (for fabrication of sensing/actuating interface electrodes).

Experimental:

All films were grown in Picosun™ R-200 advanced reactors using thermal ALD processes, and comprised alternating layers of HfO_2 and SiO_2 for a total

thickness of 100 nm. The ALD temperature was varied between 150°C and 300°C. Samples were batch processed in a wire-mesh bag (Fig S2 (d)) for full 3-D conformal multilayer encpasulation, and carefully poured on to Al foil and loosely packed for transportation. Sample handling was done using plastic-tip or vacuum tweezers. Three types of substrates were coated: 500 µm x 500 µm passive silicon die, active wireless microelectronic chiplets, and wired interdigitated electrodes. The substrates were subjected to an accelerated aging test by immersion in saline at 87 C. A subset of active microelectronic chiplets were constantly powered on using RF energy at 915 MHz. Failed samples were analyzed by scanning electron microscopy.

Results:

ALD-coated samples had an accelerated aging test survival time which can be extrapolated to > 10 years at physiologic temperatures (37°C) for passive as well as active samples (where the latter had continuous electric fields across the ALD films). Analysis of the failed samples shows areas of film breakdown at the edges, likely associated with post-encapsulation handling. There is no evidence of delamination of the ALD layer stack at the periphery of the failure, indicating that point-failure rather than a gradual degradation of the films.

Acknowledgements:

This work was supported by DARPA NESD Program Contract # N666001-17-C-4013)

2:30pm **AA1-MoA-5 Modification of Spaceflight Radiator Coating Pigments by Atomic Layer Deposition for Thermal Applications**, ***Vivek Dwivedi,*** NASA Goddard Space Flight Center*; R Adomaitis, H Salami, A Uy,* University of Maryland*; M Hasegawa,* NASA Goddard Space Flight Center

The optical and physical properties of spacecraft radiator coatings are dictated by orbital environmental conditions. For example, coatings must adequately dissipate charge buildup when orbital conditions, such as polar, geostationary or gravity neutral, result in surface charging. Current dissipation techniques include depositing a layer of ITO (indium tin oxide) on the radiator surface in a high temperature process. The application of these enhanced coatings must be such that the properties in question are tailored to mission-specific requirements.

The deposition of thin films by atomic layer deposition is a natural technological fit for manufacturing spacecraft components where weight, conformality, processing temperature, and material selection are all at a premium. Indium oxide (IO) and indium tin oxide (ITO) are widely used in optoelectronics applications as a high quality transparent conducting oxide layer. In this work, we present the thickness-dependent electrical and optical properties of IO thin-films synthesized by ALD with the aim of finding the optimum condition for coating a variety of substrates from Si(100) wafers, glass slides, and especially radiator pigments. Radiators are given surface finishes with high IR emittance to maximize heat rejection and low solar absorptance to limit heat loads from the sun. The surface finish is typically a white paint composed of nano/micron particle sized pigments with a silicate binder. It is the encapsulation of these particles that dictate the charge bleed off properties of the finished coating. Trimethylindium and ozone were used as precursors for IO, while a tetrakis(dimethylamino)tin(IV) source was used for Sn doping to produce ITO. As-deposited IO films prepared at 140 ° C resulted in a growth per cycle of 0.46 Å /cycle and relatively low film resistivity.

For the case of ITO thin-films, an ALD process supercycle consisting of 1 Sn + 19 In cycles was shown to provide the optimum level of Sn doping corresponding to the 10 wt.% widely reported in the literature. By using the inherent advantage of ALD in coating high aspect ratio geometries conformally, modification of these pigments can be accomplished during coating application preprocessing. The preprocessing is rendered directly on the dry pigment/particle before binding and not on the finished coated radiator geometry thus saving reactor volume.

Samples of our coating were recently launched into space and are currently onboard the International Space Station (ISS) as part of the one-year MISSE-10 materials test mission where the IO coated pigments are exposed to the harsh environment of space.

2:45pm **AA1-MoA-6 Novel Atomic Layer Deposition Process/Hardware for Superconducting Films for NASA Applications**, ***Frank Greer,*** *D Cunnane,* Jet Propulsion Laboratory

Future sub-millimeter telescopes and spectrometers have the potential to revolutionize our understanding of the formation of the modern universe. Sub-millimeter astronomy can probe the fine structure of the cosmic microwave background, giving glimpses into the early universe immediately following the Big Bang. Recent advances in design have enabled the production of large arrays of cryogenically cooled superconducting detectors with sufficient sensitivity for photon counting applications. Transition edge sensors (TES) and other types of detectors, fabricated from thin films of metal nitrides and such TiN, NbN, TaN, VN, and their mixtures or high temperature superconductors like MgB2, are cryogenically cooled to just below their superconducting transition temperature. Atomic layer deposition is a chemical technique that can deposit extremely conformal and uniform films with angstrom level precision that would seem ideal for deposition of films of this type. However, one significant limitation of the technique is that it is often confined to those films that can be achieved through equilibrium processes. This is a significant limitation when the material of choice, such as MgB2, which is an excellent superconducting material, is Mg deficient as deposited by conventional chemical vapor deposition and only stoichometric MgB2 is a superconductor. Superconducting MgB2 thin films have been grown using hybrid physical/chemical vapor deposition when there is an excess of magnesium in the gas phase created by evaporation of elemental magnesium in the deposition chamber. The method for doing this is to have a charge of magnesium metal that is heated above its sublimation temperature in the very near vicinity of the substrate susceptor. Unfortunately, this method is currently only appropriate for small samples (1-2" in diameter) and for thick films (100nm or thicker). To overcome these limitations, we have built a custom lid for an existing atomic layer deposition reactor was machined to include a cavity to enable magnesium evaporation during deposition. We have subsequently used this approach to deposit MgB2 thin films detectors. This presentation will focus on our thin film results from both of the nitrides and MgB2 (composition, superconducting transition temperature, morphology, etc.) as well as the possible applicability of this generalized in situ thermal evaporation technology concept to other ALD materials.

3:00pm **AA1-MoA-7 Fluoride-based ALD Materials System for Optical Space Applications**, ***John Hennessy,*** Jet Propulsion Laboratory, California Institute of Technology

In this work we describe space technology applications that plan to utilize the recent development of atomic layer deposition (ALD) processes for metal fluoride materials like MgF_2, AlF_3, and LiF. These materials are valuable optical thin films in the deep ultraviolet, and are being used at NASA JPL to fabricate protected-aluminum mirror coatings, anti-reflection coatings, and detector-integrated filter coatings. Such systems are currently being implemented in a variety of sub-orbital missions including sounding rockets, cubesats, and high-altitude balloons that are relevant to astrophysics, heliophysics, and planetary science observations. We describe how ALD thin film properties may offer performance advantages over conventional methods with respect to film uniformity, microstructure, and integration with back-illuminated imaging sensors. We also describe the development of mitigating approaches to enhance the environmental stability of typically-hygroscopic fluoride materials through the use of ALD nanolaminates and mixed-composition fluorides. The same fluoride-based ALD approach has also been exploited to perform low-temperature atomic layer etching (ALE) to enhance the optical performance of some of these devices, and to pursue strategies for the development of protective coatings for lithium metal anodes relevant to future Li-ion battery applications.

3:15pm **AA1-MoA-8 Atomic Layer Deposition of Aluminum Fluoride for use in Astronomical Optical Devices**, ***Alan Uy,*** *H Salami, A Vadapalli, C Grob, R Adomaitis,* University of Maryland*; V Dwivedi,* NASA Goddard Space Flight Center

Solid state metal halides typically have a high bandgap and low refractive index. Aluminum trifluoride (AlF_3) exhibits these properties, having a band gap greater than 10 eV and a refractive index of 1.35, making it an attractive material for thin film applications that include mirrors and optical devices [1]. Techniques to deposit thin films of AlF_3 include physical vapor deposition, sputtering, sol-gel, and atomic layer deposition (ALD) [2].

An important application of metal halides films in spacecraft missions has been for the protection of aluminum mirror from oxidation, which can severely affect overall reflectance in the far ultraviolet region. These coatings must maintain the underlying reflectivity of pure aluminum by having high transparency over the broad spectral range. To this end, AlF_3 stands out from other metal halide protective coatings, having higher transparency at the 100-200 nm wavelength region [1]. Due to long duration missions and the inability to service observatories in orbit, coatings of aluminum fluoride are also investigated for robustness and low interactions with potential foulers such as low earth orbit atomic oxygen.

These thin coatings must be pinhole free to prevent access and reaction with underlying layers.

The highly conformal dense films and thickness control by ALD are attractive for this application. In this work, the growth of AlF_3 by ALD using precursors trimethyl aluminum (TMA) and titanium tetrafluoride (TiF_4) is investigated. Deposition of AlF_3 is performed in a custom hot-wall bench-scale reactor. We have shown that our deposition system can generate growth rates of ~0.5 Å/ALD cycle at relatively low temperatures of 180 °C. Varying ALD process parameters such as the exposure and purge times of precursor were found to have interesting effects to the film growth rate, especially those concerning the precursor TiF_4. These developments also give insight into potential reaction mechanisms between TMA and TiF_4, leading towards an overall hypothesized reaction mechanism for ALD process. Furthermore, optical properties, composition, and uniformity of film are analyzed. Lastly, the generated AlF_3 film quality over months under ambient conditions for robustness also is discussed.

[1] J. Hennessy, K. Balasubramanian, C. S. Moore, A. D. Jewell, S. Nikzad, K. France, M. Quijada, J. Astron. Telesc, Instrum. Syst. 2.4 (2016) 041206

[2] M. Mäntymäki, M. J. Heikkilä, E. Puukilainen, K. Mizohata, B. Marchand, J. Räisänen, M. Ritala, M. Leskelä, Chem. Mater. 2015, 27, 2, 604-611

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