Applied Surface Science
Room 101B - Session AS-ThA

Advances for Complicated Sample Preparation Strategies and Complex Systems

Moderators: Christopher R. Anderton, Pacific Northwest National Laboratory, Michaeleen Pacholski, The Dow Chemical Company

2:20pm **AS-ThA1 Measuring Nanoparticle Properties: Are We High and Dry or All at Sea?*, Caterina Minelli,*** National Physical Laboratory (NPL), UK **INVITED**

Reliable and reproducible measurement methods for nanoparticles will significantly impact the uptake of these materials in commercial applications and allow industry to comply with regulation. However, there are significant challenges in the analysis of nanomaterials due to, among other factors, the interdisciplinary nature of the field, the lack of adequate reference materials to calibrate analytical tools and the difficulties associated both with sample preparation for analysis and the interpretation of data. Furthermore, the inconclusive outcomes of nanoparticle toxicity risk assessments can largely be traced to a failure to address these measurement challenges.

The preparation of nanoparticle samples for analysis can significantly alter both the nanoparticles themselves and the results of the analysis. Measuring colloidal nanoparticles using vacuum-based techniques is particularly prone to artefacts and irreproducibility introduced by sample preparation. In order to produce relevant and meaningful data from nanoparticle analysis it is therefore important to establish sound sample preparation protocols. It is good practice to use a combination of techniques which can be employed directly to the colloidal suspension and on the dried particles to ensure a meaningful interpretation. Examples which will be discussed include the measurement of the density of polymeric nanoparticles by small angle X-ray scattering (SAXS) and analytical centrifugation, and the analysis of the protein coatings on gold nanoparticles in liquid media (*in-situ*) and *ex-situ* with high vacuum techniques such as X-ray photoelectron spectroscopy (XPS) and low energy ion scattering (LEIS). The challenges in sample preparation for these methods and the difficulties of data interpretation will be described in detail. The *in-situ* measurement of nanomaterials in complex matrices is highly sought after by industry and regulatory bodies, but remains an unmet challenge. The potential application of new methods, such as non-linear optical techniques, will be considered.

Inter-laboratory studies enable the refinement of sample preparation protocols, which in turn have a positive impact on the broader adoption of the analytical method for nanoparticle characterisation. We will discuss the main outcomes of a VAMAS inter-laboratory study whose aims included to assess the inter-laboratory variability in the measurement of nanoparticle coatings using XPS and LEIS and identify sources of variability in sample preparation procedures. This work will directly input into ongoing efforts in ISO TC201 to standardize the surface chemical analysis of nanoparticles.

3:00pm **AS-ThA3 The Secret Life of Nanoparticles: Often Ignored Characteristics of Nano-Objects That Limit Reproducibility and an Approach to Improving Data Collection and Reporting to Address the Challenges*, Donald Baer,*** Pacific Northwest National Laboratory

The literature is filled with images of nanoparticles and nanostructured materials along with descriptions of how they were synthesized and some aspects of their new and exciting properties. However, nano-objects present fundamental synthesis, characterization, and handling challenges that are often ignored or unrecognized by parts of the scientific and technical community. The frequent tendency of such particles to interact with surrounding media and to respond to environmental changes complicates understanding their properties as a function of time in different environments but also presents interesting opportunities for the design of particles with desired time dependent properties. Particle variation due to time and environmentally dependent changes raise a number of issues associated with particle preparation for analysis, especially surface analysis. Issues include knowing the nature of changes and the rate at which they change after synthesis, during storage and processing, and in different media. This presentation will highlight some of the behaviors of nanoparticles we have observed drawing on research on Fe oxide-shell metal-core, ceria, and Ag nanoparticles. Examples will include the impact of particle structure on the dissolution and toxicity of Ag nanoparticles, the environmentally induced changes in the chemical state of ceria nanoparticles and the impact of synthesis details on the ability of iron metal-core oxide-shell particles to reduce contaminants in ground water. Some of the inconsistences in the literature are aggravated by the under-recording and under-reporting details of particle synthesis and handling. An ISO standard being developed to help address the problem will be described. This draft document includes both a standard on reporting of the preparation of particles for surface analysis and information about a range of sample preparation methods optimized for the types of information desired. One focus of the document is in on the extraction of nanoparticles from solution for analysis of surface coatings.

3:20pm **AS-ThA4 Combined XPS/ISS/UPS Study of Ultra-thin HfO_2 films on SiO_2/Si Substrateso*, Paul Mack,*** Thermo Fisher Scientific, UK

Hafnium oxide (HfO_2) films are often found in microelectronic devices, where they are used as gate dielectrics, for example. As device dimensions become smaller and smaller, it becomes necessary to make thinner HfO_2 films, which may only be a few nanometers thick. X-ray Photoelectron Spectroscopy (XPS) is an analysis technique which non-destructively provides chemical bonding information from the top few nanometres of a surface. It is the ideal technique to analyse the hafnium or silicon chemical bonding environment or to measure the thickness of these ultra-thin films. XPS cannot easily measure the coverage of ultra-thin films, however, but the complementary technique of Ion Scattering Spectroscopy (ISS) can be used for this purpose.

There is also a requirement for understanding the electronic structure of ultra-thin HfO_2 films. Ultraviolet Photoelectron Spectroscopy (UPS), using a helium discharge lamp for generate He(I) or He(II) photons (with energies of 21.2eV and 40.8eV, respectively), can be used to measure the work function of conductive films and to investigate valence electronic structure.

This talk will present data from XPS/ISS/UPS studies of a series of ultra-thin HfO_2 film films on SiO_2/Si substrates. The samples were created with varying numbers of ALD cycles, to generate HfO_2 films of different thickness and coverage. The results will demonstrate that using a complementary analytical approach, with all three techniques available on a single tool, provides a much more comprehensive analysis of the HfO_2 films than would be possible with only one analytical technique.

4:00pm **AS-ThA6 A Novel Method for Matrix Application in Matrix Enhanced SIMS Imaging*, Matthias Lorenz,*** *A.G. Shard, J.-L. Vorng, I.S. Gilmore,* National Physical Laboratory, UK

We report on a novel method for controlled and versatile application of matrix compound for the purpose of matrix enhanced secondary ion mass spectrometry (ME SIMS). General applicability of this approach for ion signal enhancement of drug molecules and endogenous compounds in drug dosed tissue homogenate is demonstrated.

A major problem for SIMS imaging in life-sciences is the signal-limited spatial resolution and matrix effects that suppress ion yields. In severe cases, the ion signal may be lost all together. This leads to the adage that not seeing a molecule in SIMS does not mean it is not there. One route forward is to use a molecule to enhance the signal as done in matrix assisted laser desorption/ionization (MALDI). However, it is well-known that this causes redistribution of analytes (such as drugs) over tens of microns. This circumvents the resolution benefit of SIMS over MALDI. Furthermore, methods used for MALDI are not suitable for 3D imaging, where the matrix layer would be sputtered away. We report on a novel technique for the controlled application of matrix compounds specifically for ME SIMS that overcomes these two major barriers.

The new approach provides high flexibility and precise control of the timing and amount of material applied. It is applicable for a wide range of matrix compounds. The general approach and critical instrumental parameters of the technique will be discussed, and its applicability for the enhancement of SIMS ion signals will be shown on examples of drug compounds and drug molecules embedded in tissue homogenate. We show that ion signals of clozapine could be enhanced by a factor of 3 for the protonated molecule $[M+H]^+$ by adding 2,5-dihydroxybenzoic acid (2,5-DHB), a common matrix compound used in MALDI. The $[M+H]^+$ ions of the drug molecules chloroquine and tamoxifen show an enhancement with 2,5-DHB matrix application. A factor of 7 enhancement of clozapine could be achieved with 3-nitrobenzonitrile (3-NBN), a species utilized for primary ion formation in the matrix assisted ionization vacuum (MAIV) technique. The abundance and intensity of lipid related signals (e.g., the phosphocholine fragment at *m/z* 184) in the spectra are significantly enhanced for the analysis of the tissue homogenate. The addition of formic acid shows another example for signal enhancement using the new approach, with an increase of the

$[M+H]^+$ signal of the drug molecule by a factor greater than 3 and of the phosphocholine signal (*m/z* 184) by a factor of 6.

4:20pm **AS-ThA7 ToF-SIMS Imaging of Bee Brain Tissue – Comparing Lipid Distributions and Varying Sample Preparation Methodologies***, **Jordan Lerach**, E. Amsalem, C.M. Grozinger,* The Pennsylvania State University

Time-of-flight secondary ion mass spectrometry (ToF-SIMS) with cluster-based primary ion sources enables researchers to elucidate molecular information from complex samples with sub-micron imaging resolution. This technique is becoming more commonly applied to complex biological systems due to its excellent molecular imaging capabilities. The following research details, with chemical specificity, the location of molecules of interest in brain tissue of the common eastern bumble bee (*Bombus impatiens)*. Microtomy was used to create thin tissue sections of both frozen-hydrated and freeze-dried tissues and the differences in the data sets are reported. A ToF-SIMS instrument with a Bi_n^{q+} primary ion source selected for Bi_3^{++} ions is used for analysis. This ion source is shown to produce large molecular ions in excess of 1,000 amu on the tissue samples which yields information from larger biomolecules such as lipids. In this analysis specific attention is paid to the lipid distribution since site-specific chemical imaging of lipids in the brain tissue remains relatively unexplored.

4:40pm **AS-ThA8 Understanding Matrix Effects in Mass Spectrometry***, **Amy Walker**, L.D. Gelb,* University of Texas at Dallas

Chemical imaging methods, including imaging mass spectrometry (MS), are becoming widely used for the analysis of a variety of samples from biological tissues to electronic devices. A significant barrier to wider adoption of imaging mass spectrometry is the presence of matrix effects which complicate quantitative analysis. Interactions between an analyte molecule and its surroundings (the “matrix”) can substantially alter both the yield and type of ions observed. These matrix effects result in both significant nonlinearity of signal intensity with concentration and changes in the characteristic spectrum of a given species with environment. We present progress towards the quantitative extraction of chemical concentration profiles, component spectra, sample topography, and other information from imaging mass spectrometry data in the presence of matrix effects. Our approach is based on maximum *a posteriori* (MAP) reconstruction against physically motivated models rather than statistical dimensionality-reduction techniques such as Principal Components Analysis. We demonstrate our methodology using several different samples as well as synthetic data sets. These include systems that demonstrate “weak” matrix effects, such as mixed self-assembled monolayers, and “strong” matrix effects such as those observed in ionic liquid matrix enhanced secondary ion mass spectrometry.

5:00pm **AS-ThA9 Reducing Matrix Effects in Organic Secondary Ion Mass Spectrometry***, **Lars Breuer**, H. Tian, N.J. Popczun,* The Pennsylvania State University*; A. Wucher,* University of Duisburg-Essen, Germany*; N. Winograd,* The Pennsylvania State University

Secondary ion mass spectrometry (SIMS) is a powerful tool for surface analysis. With the development of cluster ion beams, this technique now has the capability to analyze organic materials while maintaining molecular information of the analyte. A challenging aspect in SIMS applications in multi-components systems are so called *matrix effects* in the ionization probability of sputtered material. Unfortunately, there is no theory to date which is capable of predicting these matrix effects. Results are presented here to show one physical and one chemical approach to address and reduce matrix effects in an organic model systems of Irganox 1010 and 1098.

The first, and perhaps most straightforward approach in overcoming matrix effects is to decouple the ionization from the sputtering process. For this purpose, the plume of sputtered material above the sample, mainly consisting of neutral species, is intersected with an intense ultrafast laser pulse in the near infrared region with power densities up to several 10^{15} W/cm^2. This pulse ionizes neutral particles within the plume and makes their detection feasible

The second approach presented is based upon the idea of enhancing protonation at the bombardment sites. HCl doped Ar_n^+ gas cluster ions, in which the HCl molecules are incorporated into the gas clusters, are used as the primary ion beam. During analysis, H_2O is precisely leaked into the analysis chamber while the sample is cooled with liquid nitrogen. In this way, a thin ice overlayer is formed at the sample surface to facilitate the dissociation of the HCl molecules incorporated in the Ar_n gas clusters. The free hydronium ions become available at the impact site, which aid the protonation of intact molecules. During the entire analysis, a dynamic equilibrium between deposition and sputtering of ice is well maintained to yield a quantitative depth profile.

5:20pm **AS-ThA10 Image Fusion for Improving the Visualization of Elemental and Isotopic Distributions in SIMS***, **Jay Tarolli**, B. Naes, B. Garcia, A. Fischer, D. Willingham,* Pacific Northwest National Laboratory

While secondary ion mass spectrometry (SIMS) is a technique that offers a substantial amount of chemical information of an analysis area, it comes with inherent limitations that often reduce the signal-to-noise ratio of desired species as well as the achievable spatial resolution. A growing approach to overcoming these limitations is to acquire complementary information from other analytical imaging techniques, such as optical and electron microscopy. Image fusion is a post-acquisition data analysis technique that has been recently applied to new and more diverse SIMS experiments in order to improve the perceived spatial resolution, intensity, and contrast of chemical images. The basis of image fusion is to combine information from two or more input images in order to create an output visualization that better represents the analysis area than any of the input images could alone. Thus, multimodal imaging analyses that incorporate SIMS and a second higher resolution analytical technique, followed by post-acquisition image fusion, are able to provide a representation of chemical information with greater detail at a smaller scale.

In this work, a new source of higher resolution data, X-ray energy-dispersive spectroscopy (EDS), is explored to improve the visual quality of SIMS images, combining elemental information with chemical information. First, a workflow was developed to register and fuse EDS images of an Al-Si-Cu alloy at various microscope magnifications with dynamic SIMS images to better visualize the localization of Cu and Si domains. A new implementation of image fusion was then developed to improve the screening process of U-bearing particles. In this case, elemental information provided by EDS is used to improve the spatial resolution of uranium isotopic distributions in order to differentiate particles which may potentially be enriched. These particles can then be screened individually to verify the isotopic distributions. In this case, image fusion has been applied not simply in a proof-of-concept scenario, rather an implementation that improves an existing process in order to obtain SIMS results with higher accuracy and precision.

5:40pm **AS-ThA11 Evaluating the Utility of Uranium-Molybdenum Foils as Nuclear Fuels via Elemental and Isotopic Imaging***, **David Willingham**, J. Tarolli, B. Naes, M. Rhodes, M. Dahl, A. Guzman, D. Burkes,* Pacific Northwest National Laboratory

We aim to characterize the elemental and isotopic composition of uranium (U) metal and U metal alloys by electron microscopy (EM) and secondary ion mass spectrometry (SIMS). This type of characterization is important in understanding the behavior and performance of nuclear fuels and targets, and could potentially be utilized to interrogate processing history of the material. One example of such nuclear alloys is the uranium-molybdenum (U-Mo) system, development of which is being actively pursued throughout the world for use in research and test reactors (NA-23 Reactor Conversion Program), light water power reactors (DOE-NE Accident Tolerant Fuel), and pulse reactors (DoD – Army).

Previous EM characterization of approx. 19.75% enriched ^{235}U-10wt% Mo fuel foils produced for the NA-23 Reactor Conversion Program revealed a complex grain structure of coarse, highly elongated regions interspersed with finer, more equiaxed grains. The distribution of grains was also organized within regions containing significant Mo variation produced during casting of this particular alloy. During post-irradiation examination, these regions and structures have been observed to behave differently depending upon the irradiation conditions that the fuel was subjected to. Elemental and isotopic heterogeneities in the fuel, particularly at boundaries between grains, have been hypothesized to lead to non-uniform swelling regions (i.e., volume growth) within the fuel. Understanding the elemental and isotopic distribution of alloying metals and other impurities is important to reasonably predict behavior of the fuel in a particular reactor system, ultimately enabling successful qualification for its use.

SIMS image analysis revealed several key characteristics of the U-Mo foil system. First, Mo rich grains could be observed by SIMS imaging. These grains are highly elongated along the length of the foil. Secondly, carbon inclusions, likely a result of U carbides, were found in the SIMS images. These inclusions can be seen to track with the previously observed Mo rich elongated grains. Finally, the U within the foil is much more homogenized than the Mo and appears to be much less mobile. The $^{235}U/^{238}U$ is consistent with the known value at approx. 20% enrichment of ^{235}U and the

U isotopic distribution is homogenous in all regions of the U-Mo foil. It is, therefore, likely that non-uniform swelling of these foils under irradiation is due primarily to U-Mo elemental heterogeneities rather than U isotopic variations.

6:00pm **AS-ThA12 Investigation of the Interaction Between a High Poly Vinylpyrrolidone Content Silicone Hydrogel Contact Lens and a Natural Humectant using Surface Imaging Techniques***, **Katarzyna Wygladacz**, D.J. Hook,* Bausch + Lomb

Background: Optimum surface wettability and high water content are both important factors that can influence successful contact lens wear. In the case of the silicone hydrogel contact lens, samfilcon A, polyvinylpyrrolidone (PVP) was engineered into the material to increase the water content and provide a wettable lens surface. As a compliment to high level of PVP in the lens chemistry another way to improve lens wettability is to take advantage of interactions between the lens material and the lens care solution. This study assessed the interaction of hyaluronate (HA), a natural humectant, present in Biotrue multi-purpose solution (MPS) with the high PVP-content samfilcon A lens, using multiple analytical techniques.

Method: X-ray Photoelectron Spectroscopy (XPS) characterization was used to confirm the presence of HA on the lens surface.The distribution of HA over the samfilcon A surface was assessed by quantitating lens surface roughness (RMS), before and after incubation with 0.1% (w/v) HA by atomic force microscopy (AFM) imaging. Confocal laser scanning (CLSM) and differential interference contrast (DIC) microscopies were used to characterize the association of HA to the surface of samfilcon A lenses after exposure to 0.1% (w/v) HA and HA present in Biotrue MPS.

Results: Differences in the XPS C1s spectra recorded for samfilcon A before and after exposure to 0.1% (w/v) HA were detected. Samfilcon A surface roughness (RMS) was 2.5 ± 0.4 nm before exposure to HA and was significantly decreased after incubation with 0.1% (w/v) HA, (RMS=0.6 ± 0.1nm; $p<0.05$). CLSM and DIC imaging illustrated a comparable confluent, stained HA network that extended across the entire surface with 0.1% (w/v) HA and commercial HA-containing MPS.

Conclusion: XPS analysis show evidence for samfilcon A surface modification with hyaluronate. CLSM and DIC imaging offered a comprehensive view of the lens surface and demonstrated an extensive coverage of HA on samfilcon A. AFM measurements confirmed that HA adsorption reduced roughness of the lens surface. Together, the combination of imaging techniques provided a unique picture of the interaction of HA and PVP containing silicone-hydrogel lenses.

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