Characterization of extreme ultraviolet laser ablation mass spectrometry for actinide trace analysis and nanoscale isotopic imaging

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We demonstrate a new technique for trace analysis that has nanometer scale resolution imaging capability: Extreme Ultraviolet Time-of-Flight Laser Ablation Mass Spectrometry (EUV TOF). We describe the characterization of this technique and discuss its advantages. Using the well-standardized NIST 61x glasses, the results show the EUV TOF spectra contain well defined signatures of U, Th, and their oxides, with far fewer spectral interferences than observed in Time-of-Flight Secondary Ion Mass Spectrometry (SIMS TOF). We demonstrate that the ratio of U and Th ions to the oxide ion signatures is adjustable with EUV laser pulse energy. Sample utilization efficiency (SUE) which measures the ratio of detected ions to atoms in the ablated volume was used as a measure of trace analysis sensitivity of EUV TOF. For U and Th, SUE is 0.014% and 0.017%, respectively, which is comparable to SIMS TOF in the same mass range. In imaging mode EUV TOF is capable to map variations in composition with a lateral resolution of 80 nm. Such high lateral resolution enabled mapping of the isotope distribution of $^{238}$U and $^{235}$U in closely spaced micron-size uranium oxide particles from isotope standard materials. Trace elemental sensitivity and nanometer spatial resolution gives EUV TOF great potential to dramatically improve the state-of-the-art laser ablation/ionization mass spectrometry and elemental spectro-microscopy for applications such as geochemical, forensic and environmental analysis.

Introduction

The requirements to identify trace and impurities and map elemental composition in solid samples with high sensitivity and high spatial resolution has driven the implementation of analytical methods such as atom probe tomography (APT), secondary ion mass spectrometry (SIMS), scanning transmission electron microscopy energy dispersive X-ray spectrometry (STEM-EDX), and laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS). These techniques span a wide range of spatial resolution (nm to 100’s of μm) and sensitivity (weight percent to parts per trillion). Ideally, a micro-analytical technique will probe a small volume to keep the spatial resolution as high as possible with near perfect sampling efficiency to keep detection limits as low as possible. This is however very challenging to achieve because the detection of ions scales with the probed sample volume.

We have recently demonstrated it is possible to map molecular composition in organic samples with three dimensional nanoscale spatial resolution and high sensitivity with mass spectrometry when using a very compact extreme ultraviolet (EUV) laser operating at 46.9 nm wavelength (26.4 eV photon energy) for ablation and ionization. The high localization of EUV photon energy is possible because the EUV photons are strongly absorbed by direct photoionization of dielectrics made it possible to ablate craters micron deep at threshold fluences of ~0.1 J cm$^{-2}$ (peak intensity = 70 MW cm$^{-2}$), 20–40× smaller than when using ultraviolet lasers for ablation.

EUV TOF is conceptually similar to standard laser ablation methods although it does not require an additional external ionization source as in LA-ICPMS. In this aspect it is also similar to SIMS. In addition, the EUV laser light can be focused down to approximately 100 nm spots, roughly one to two orders of magnitude improvement over most commercial laser ablation systems and comparable with nanoSIMS, which has demonstrated a spot size of ~50 nm. Research laser ablation systems have used near-field optics to focus fs-lasers down to...
create craters with diameter down to 30 nm, but coupled with an external ICPMS these systems only provided analytical results on bulk (not trace) elements when the craters were increased to 800 nm.

Herein, we describe the characterization of EUV TOF for elemental analysis. The mass spectra, taken from NIST 61x glasses, demonstrate that EUV TOF can ionize the matrix elements in the glasses and many of the trace elements going from Rb, and Cs, all the way up to higher masses such as Th, and U. We show evidence that the distribution of species extracted from the EUV plasma, atomic and molecular ions, depends on the EUV fluence offering added versatility for mass spectrometric detection. We characterize ion formation and measure sample utilization efficiency (SUE), focusing primarily on uranium and thorium due to their high atomic mass and significance in nuclear materials. By scanning micron-sized lines made out of nickel, we are able to establish EUV TOF has a lateral resolution of 80 nm. Finally, we apply EUV TOF to map the composition of natural and enriched uranium oxide particles, thereby demonstrating that this system can simultaneously have nanoscale spatial resolution and high sensitivity in isotope analysis.

Methods

EUV TOF, conceptually similar to standard laser ablation/ionization, was carried out using the set up schematically shown in Fig. 1. This system uses a compact EUV laser for ablation and ionization coupled with a time-of-flight mass spectrometer. The EUV laser produces ~10 μJ pulses, ~1.5 ns in duration, at a wavelength of 46.9 nm. It is based on the concept of laser amplification in Ne-like Ar ions in a highly ionized capillary discharge plasma column first demonstrated at Colorado State University. The laser pulses are guided by two grazing incidence gold coated toroidal mirrors into the interaction chamber to illuminate a zone plate that focuses the laser beam with a Gaussian profile onto the sample. The zone plate was designed to have a 200 nm outer zone width and 50 μm central aperture for ion extraction. When illuminated at λ = 46.9 nm, its focal length is 2.13 mm and confocal parameter is 8.6 μm.

The zone plate has an efficiency of 10% when operating in first order. Taking the zone plate efficiency into consideration, the fact that only a portion of the EUV beam illuminates the zone plate and the reflectivity of the grazing incidence mirrors, the pulse energy reaching the sample is 1.5 × 10⁻³ of that at the laser output. The laser pulse energy is measured at the start and end of every experiment with a photodiode and is also monitored pulse by pulse with a custom-built cylindrical photoionization detector. Adjustment of the laser pulse energy with a variable pressure argon gas cell makes it possible to control the laser fluence at the sample. Alternatively, the zone plate can intentionally be defocused by as much as 20 μm before the laser pulses no longer ablate the glass samples. For elemental and isotopic mapping, the sample positioning was controlled by piezoelectric motors with nanoscale accuracy, with 50 nm increments used during the resolution analysis and uranium isotope imaging.

The results described herein were obtained by using a 6 kV accelerating potential applied between the sample and ground grid. The ions from the EUV laser produced plasma were extracted through the zone plate, reflected at the end of the TOF chamber, and detected on a 40 mm Dual Microchannel Plate (MCP) detector. The TOF chamber was kept at a pressure of ~10⁻⁷ Torr during measurements. The mass resolution of the TOF mass spectrometer was previously found to be m/Δm = 1100. The primary factors limiting this system’s mass resolution are the time it takes to accelerate ions out of the plasma due to high plasma density and Debye sheath penetration, and counteracting temporal compression efficiency of the reflectron.

Data acquisition is automated by a custom-built LabVIEW program. The subsequent analysis in Matlab allows averaging together spectra from a single layer of ablated material, spectra from a single crater that was formed with multiple pulses, or any combination thereof. The mass range is calibrated using a quadratic least-squares fit that uses the arrival time of two or more obvious mass peaks and correlates their arrival times with known mass values for those isotopes.

The SIMS spectra were collected using a SIMS TOF instrument (TOF-SIMS5, IONTOF GmbH, Münster, Germany) in Environmental Molecular Sciences Laboratory (EMSL), located at Pacific Northwest National Laboratory (PNNL). A 25 keV pulsed Bi⁺ ion beam was used as the analysis beam, and the analysis area was 200 × 200 μm². The beam current was about 1.0 pA at a repetition rate of 10 kHz. The data collection time for each spectrum was about 600 s. Charge compensation was used for all depth profiling measurement. The details for the adjustment of charge compensation and additional information for SIMS TOF measurement can be found in a previous publication. To get the sputtering rate, the 25 keV pulsed Bi⁺ ion beam was scanned on a 25 × 25 μm² area on the glass sample. The beam current was about 5.0 pA at a repetition rate of 50 kHz. The sputter time was 3600 s to ensure a reasonable depth of the crater can form. The depth of the sputter crater was measured using a Dektak 6M stylus profilometer. For convenience, a constant sputter rate was adopted in each measurement.
A mass spectrum from NIST 610 was also collected using a modified CAMECA ims-4f in dynamic mode. A portion of a NIST SRM 610 sample was mounted in epoxy and coated by Au prior to analysis. The ims-4f was operated in ion microprobe mode using a Kohler illuminated, 100 nA O⁻ primary ion beam with an impact energy of 18.5 keV. The circular field of view was 150 µm in diameter; a 750 µm field aperture was utilized following a 10 minute pre-sputtering event. The mass step interval was 0.01 with a dwell time of 0.1 s, the scan range for the acquired spectrum was 200 to 300 Da.

We tested atomic and molecular ion formation and measured sample utilization efficiency (SUE) with the NIST 61x series of glasses. Specifically, we ablated NIST 611, 613, 615, and 617, doped with over 60 different elements in nominal concentrations of 500, 50, 5, and 0.05 µg g⁻¹, respectively. These are well-known and well characterized laser ablation standards²⁸ which provide the ability to perform consistent analytical comparison between instruments. For EUV TOF analysis, sample preparation consisted of depositing ~30 nm of 99.99% pure aluminum by thermal evaporation on each glass slide to minimize charge buildup and to create a uniform electric field that facilitates ion extraction. Due to significance in the nuclear fuel cycle and in nuclear forensics, we focused on uranium and thorium as a test elements. We measured the crater volumes for the SUE analysis with a Zygo New View 7300 Scanning White Light Interferometer (SWLI). Due to limited lateral resolution of the SWLI, a rectangular pattern was made by the significant lateral overlapping of individual craters. The overlapping rectangular pattern of craters was made using 1200 laser pulses in a 20 by 20 array with each location receiving 3 laser pulses. The centers of the ablation craters were displaced by 500 nm. The mapping time took 34 minutes with the laser operating at 0.6 Hz repetition rate. The resulting rectangular crater pattern had ~10 µm on its sides and around 40 to 200 nm in depth depending on laser energy used. For the SUE calculation of detected ions, the mass spectrum from each single shot ablation was background-adjusted to bring the baseline signal to zero. The mass peak corresponding to ²³⁸U was then integrated using a Riemann sum of 1 ns bins. This integrated voltage was divided by the measured MCP gain of the system, 18.5 mV per ion, to produce the number of detected ions. MCP gain was assessed by processing data sets of NIST 611 SUE analysis by attenuating laser fluence. This is the same data presented in Fig. 6. Plotting a histogram of counts that correspond to zero and single ion detection events resulted in a single ion count being equivalent to an MCP signal of 18.5 mV.

We measured the lateral resolution of EUV TOF by mapping composition on a sample that consisted of interlaced nickel comb structures of different widths made at the Center of X-Ray Optics at Livermore Berkeley National Laboratory by electron beam lithography. The metallic lines of Ni were 1 µm wide and 100 nm tall each. As a means to demonstrate isotopic imaging with nanoscale resolution, uranium oxide particles of different isotope compositions placed in close proximity were ablated. This sample consisted of a single particle of CRM 129A (natural abundance) placed adjacent a single particle of CRM U200 (20% ²³⁵U, 80% ²³⁸U). Scanning electron microscope (SEM) images were taken with a JEOL-JSM 6500F SEM at a 25 000x magnification and 1.5 kV beam voltage.

**Results and discussion**

**Mass spectrometry analysis**

Fig. 2 shows the EUV TOF spectra collected for each of the four NIST 61x glasses. The full mass spectrum for each glass is broken up into four mass ranges, helpful to plot the signal on the appropriate linear axis. Spectra from all four glasses are presented to provide a rough estimate of the abundance sensitivity and to distinguish elemental ion peaks from matrix molecular peaks. The low to mid mass spectra, panels A and B in Fig. 2, show intense signals from the bulk glass components. While not definitively assigned, possible molecular ion peak candidates are displayed on the figure. Unidentified molecular interferences are marked with an asterisk. The limited dynamic range of the TOF detection system precludes measuring relatively weak doped element signals in the midst of large matrix signals. The only non-matrix peaks in the low to mid mass ranges are from rubidium and cesium. As the largest group I elements, Rb and Cs have low oxygen bond strengths and the lowest ionization potentials in the periodic table. As a result, these elements are efficiently ionized and detected with the EUV TOF system, even as trace components.

The high mass range, panels C and D in Fig. 2, is not hindered by large molecular interferences from the matrix, rendering elemental contributions from the lanthanides, lower P-block, and actinides in NIST 611 clearly visible. Some small signals are evident for NIST 613, but for the most part the nominal 50 ppm concentration of U and Th in NIST 613 is near the detection limit of the current EUV TOF system. This is a rough estimate as we did not attempt a more qualitative determination of detection limits. Some of the mass peaks in Fig. 2C appear asymmetric or otherwise noisy compared to peaks in A, B and D. This could be the result of matrix interferences occurring at similar masses or it could be due to timing irregularities from charging of the substrate, but it is unclear due to the limited mass resolution. Data from NIST 615 and 617 are plotted to give clear indication of matrix peaks that are essentially invariant across the four glasses.

For orientation of EUV TOF within the larger field of surface elemental analysis, Fig. 3 presents SIMS TOF and EUV TOF scans of NIST 610/611. Comparing EUV TOF to SIMS TOF is helpful to partially normalize ion detection as both instruments utilize TOF mass spectrometers such that differences in the ionization characteristics become evident. SIMS TOF is also a standard means for multi-element analysis of surfaces and the comparison is helpful to orient the EUV TOF data within the larger field of surface elemental analysis. SIMS TOF has been shown to be excellent in the analysis of glasses, having detection limits of some elements ranging from 10 ppb to 10 ppm²⁹

The EUV TOF data is repeated from the NIST 611 data shown in Fig. 2. Again, the full spectra are split into four mass ranges for optimal visualization. Panels A and B utilize logarithmic scales (an artificial offset was added to the EUV data to keep the baseline positive) while panels C and D revert to linear scaling.
The first conclusion of the SIMS TOF and EUV TOF comparison is the difference in the number of molecular ion interferences in the whole mass range (Fig. 3). The EUV TOF spectrum has significantly fewer molecular ion interferences compared to the SIMS TOF which shows a peak at nearly every nominal mass. The difference in molecular interferences is likely a result of the differences between ablation and sputtering processes.

The gray bars in Fig. 3C and D represent calculated relative elemental/isotope signal intensities for NIST 611 based on the known content and natural (depleted for uranium) isotope ratios. The calculated spectrum was scaled empirically to match the experimental spectra. Both the SIMS TOF and EUV TOF data show decent agreement with the known composition in the rare earth range. However, the SIMS TOF spectrum shows relatively less intensity for the bottom P-block elements (Tl, Pb, Bi) and the actinides (Th, U). It has only weakly discernable peaks for Th and U, but the ThO and UO peaks are recognizable with ThO2 and UO2 also visible. In contrast, the EUV TOF spectrum has prominent Th and U signals and P-block elements that match the calculated gray bars more closely. The EUV TOF spectrum also shows significant ThO and UO peaks (some UO2). The distinct feature of having fewer interferences in EUV TOF compared to SIMS TOF observed within the high mass range of Fig. 3 will be advantageous for high mass isotope ratio analysis as carried out with magnetic sector mass analyzers.

Fig. 4 compares the EUV TOF mass spectrum with one collected under dynamic SIMS conditions on a magnetic sector instrument. The axes of the two spectra are plotted such that the ThO peaks are of equal intensity. In the dynamic SIMS spectrum the lower P-block elements are diminutive, but the elemental Th and U are prominent. However, the ThO and UO still dominate with ThO2 and UO2 present, likely a result of the O– primary ion.
beam. In contrast, the EUV TOF spectrum is dominated by elemental U and Th. The dynamic SIMS measurement seeks to increase the yield of atomic ions by eroding the surface with a high flux of primary ions, essentially adding energy to break molecular bonds prior to ionization. In general, it is difficult and time consuming to adjust the SIMS parameters that affect molecular fragmentation. In contrast the EUV TOF ablation/ionization process creates a plasma in which a larger relative proportion of surface elemental ions can be extracted. Furthermore, the high localization of the EUV laser energy results in ablated craters with no indication of subsurface damage.

The laser pulse energy and intensity influence the EUV produced plasma properties, and consequently the relative atomic and molecular ion abundance in the plasma. Instead of measuring the plasma temperature or density, we directly measured the relative intensity of element and oxide peaks. Fig. 5A shows the high mass spectrum of NIST 611 taken at various laser intensities. It is clear from the spectra and Fig. 5B that the elemental (Th, and U) peaks increase linearly with increasing laser energy. The oxide peaks (ThO, and UO) also increase with increasing laser pulse energy, but at a slower rate. Fig. 5B also plots the oxide to element signal intensities as a function of laser energy. It can be concluded that higher laser fluence creates plasmas with characteristics that favor elemental ion formation whereas lower fluence leaves more elemental oxides. Similar experiments (not shown) conducted at constant laser pulse energy, but with the sample displaced.

Fig. 3  Mass spectrum of NIST 610 generated with both EUV TOF and SIMS TOF. The panels (A–D) present portions of the full mass spectra. Panels (A and B) plot spectra on logarithmic scales with the EUV TOF data offset to remain positive. Panels (C and D) plot spectra on linear scales and the gray bars indicate nominal elemental content of NIST 610, scaled to match experimental data in the lanthanide region.
from the zone plate focus, in effect changing the density of photons at the sample, produced entirely consistent results, i.e. a linear change in signal intensity with photon flux. It is compelling that the elemental to molecular ratios can be adjusted with laser fluence implying that even better analytical performance for elemental analysis could be had with higher EUV laser energy.

Sample utilization efficiency

High SUE is important when measuring microscopic and limited material samples. For atom limited samples, higher SUE will directly result in lower statistical uncertainty on analytical measurements. Consequently, SUE is a valuable metric for microanalytical techniques. SUE, defined here as the number of ions detected compared to number of atoms removed, is suitably measured with post-ablation crater volume measurements. Fig. 6 shows the measured uranium ions against the subsequently measured crater volume. With the known concentration of uranium in NIST 611 glass, the crater volume is directly converted to a count of uranium atoms ablated and the efficiency calculated as the ratio of the measured ions to ablated atoms. Over the laser energy range measured in Fig. 6, the relationship of detected U ions to ablated atoms is highly linear and SUE was calculated from the slope of this relationship.

At 0.014% for $^{238}$U and 0.017% for $^{232}$Th, the SUE of EUV TOF is essentially the same as we measured for U and Th with SIMS TOF. Based on crater volume measurements for the SIMS TOF analysis of NIST 611 glass we calculated a SUE of 0.013% for this method. As another point of reference, quadrupole ICPMS SUE is around 0.0001%,31,32 Dynamic SIMS with magnetic sector instruments have produced uranium SUE for NIST 610 up to 0.7%.33 Laser ablation ICPMS analysis of NIST 610 with a magnetic sector ICPMS measured SUE of uranium above 1%.3 The fact that SUE for EUV TOF and SIMS TOF obtained from U and Th were nearly the same indicates that the efficiency for both could be limited by the mass spectrometer efficiency and not the ionization efficiency of the source. The SUE of Cs and Rb using the EUV TOF are both estimated to be above 1%, and this is most likely due to different ionization energies of the isotopes. It is reasonable to speculate that percent level SUE of U and Th could be obtained with an EUV laser for ablation and ionization with a more efficient magnetic sector instrument for mass analysis.

Fig. 4 Comparison of EUV TOF and dynamic SIMS in the high mass range showing intense U and Th peaks and their oxides. Both spectra are normalized to the oxide peaks.

Fig. 5 Partial mass spectra for NIST 611, panel (A), show changes in atomic and molecular ion peaks with laser energy. Panel (B) plots the U and Th signal intensity (integrated peaks extracted from data in panel (A)) as a function of laser energy. Panel (B) also plots the UO$^+$/$U^+$ and ThO$^+$/Th$^+$ ratios from the NIST 611 glass as a function of laser energy.

Fig. 6 Plot of uranium atoms measured at various laser fluence conditions against the resulting crater volume (top axis). The crater volume was used to calculate the number of ablated uranium atoms (bottom axis) and the efficiency is the ratio of the measured to ablated uranium atoms.
Lateral spatial resolution

The EUV TOF is specifically designed for composition imaging. In previous work, we showed the method can map the distribution of organic molecular components with a lateral spatial resolution of 75 nm and a depth resolution of 20 nm.\(^7\) Composition mapping is implemented by displacing the specimen across the focused EUV laser beam. The highest lateral spatial resolution is obtained by attenuating the laser fluence to reduce the diameter of the ablated spot to values at which the ion peaks are 5\(\times\) the noise floor in the mass spectrum.

We employed the same methodology as with organics to evaluate the lateral resolution of EUV TOF for composition mapping of inorganic samples. The sample used for this experiment consisted of a comb of nickel lines 1 \(\mu\)m wide and 100 nm thick (Fig. 7A). The lines are sharp and well defined as shown in Fig. 7B. The line edge roughness (LER) was measured on an SEM image by detecting the 50% point on the nickel edge over a distance of 2.5 \(\mu\)m along the edge. The LER is calculated to be 29 nm by finding the 3\(\sigma\) of the collected data points along the edge.\(^34\) The sharpness of the edge was measured using the SEM image of Fig. 7B by finding the average distance between the 20% and 80% intensity points on the nickel edge averaged over a 2.5 \(\mu\)m distance along the edge. The edge sharpness was calculated to be 21 nm \(\pm\) 4 nm.

Fig. 7C shows the distribution of the major isotope of Ni at 58 Da on a region near an edge of a Ni line in the comb. This composition image was obtained from the analysis of mass spectra resulting from the ablation of the sample in the form of a 9 by 20 grid in which the step size is 50 nm. It is then averaged along one direction to form the line scan shown in Fig. 7D. These data points are plotted, normalized, and are fitted to an edge spread function (ESF), which is the standard method for determining lateral resolution.\(^35,36\)

\[
\text{ESF} = I_{\text{max}} + \frac{I_{\text{max}} - I_{\text{min}}}{2} \left( 1 + \text{erf} \left( \frac{x - \mu}{\sigma \sqrt{2}} \right) \right)
\]

where \(I_{\text{max}}\) and \(I_{\text{min}}\) are the normalized maximum and minimum mass peak intensities in the line scan.

A fit of the data of Fig. 7D using \(I_{\text{max}}/I_{\text{min}} = 350\) yielded \(\sigma = 47\) nm and \(\mu = 0.63\ \mu\)m. The lateral resolution taken as the distance between the 20% and 80% relative intensity points on this knife-edge ESF curve is 80 nm which is very similar to previously obtained results.\(^7\)

Imaging of uranium oxide particles

Nanoscale resolution images with isotope differentiation were obtained by ablating adjacent placed, micrometer-sized uranium oxide particles with differing isotope compositions. The particle pair was first scanned with a low-resolution 10 \(\times\) 10 pixel scan with a 0.5 \(\mu\)m step size, Fig. 8A. The ablation craters left behind by this coarse scan are visible on and around the particles as shown in the SEM image, Fig. 8B. A small portion of the particle pair was then scanned in a 30 \(\times\) 30 grid pattern with 3 laser pulses per location and with a 50 nm step size. The red box in Fig. 8B indicates the area where the high resolution raster took place. Fig. 8C shows the averaged intensity map of \(^{238}\text{U}\) (signal averaged over the three co-located sequential shots and the \(^{238}\text{UO}\) and \(^{238}\text{UO}_2\) peaks). This process is repeated in Fig. 8D showing the corresponding image for \(^{235}\text{U}\) and its oxides. Although the dynamic range limitations of MCPs make it difficult to conduct precision uranium isotope ratio analysis, an initial estimate of the ratio can be produced from the data in Fig. 8C and D. Averaging the ratios from individual pixels from the enriched particle returns a \(^{235}\text{U}/^{238}\text{U}\) ratio of 0.248 \(\pm\) 0.006 evenly distributed throughout the area of the scanned particles. The expected value from the U200 standard is 0.2513 \(\pm\) 0.0003.

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Fig. 7 Lateral resolution assessment. (A) Scanning electron microscope (SEM) image of the nickel comb structure. (B) SEM image of a single nickel line. (C) Composition image comprised of 9 adjacent passes from substrate on the left to Ni on the right depicting the distribution the main Ni isotope. (D) Column-averaged data. (E) Normalized column-averaged data fitted with an error function and showing the 20–80% distance corresponds to 80 nm.
Conclusions

We described the characterization of EUV TOF for trace analysis, and quantified the sample utilization efficiency using NIST 61x glass standards. The results showed that EUV laser ablation can effectively atomize and ionize elements from these complex matrices while allowing relatively few molecular ion interferences throughout the mass range. This is in contrast to the SIMS TOF analysis of the same samples which have numerous interferences throughout and a diminished elemental signal at higher masses. The data also indicate that tuning of the EUV laser fluence can shift the distribution of detected ions with higher laser fluence favoring atomic over molecular ion formation. The low concentrations of the NIST 61x glasses ranging from 500 ppm to 0.05 ppm and their low surface roughness enabled us to accurately measure the SUE of EUV TOF as 0.014% for uranium. This is comparable to SIMS TOF and may be limited by the mass analyzer rather than the ionization source.

The high localization of the EUV light in materials coupled with its distinct interaction gives EUV TOF unique capabilities for mapping composition at nanoscale dimensions. The results showed that EUV TOF achieved a lateral resolution of 80 nm when mapping composition variations across a metal/dielectric interface, a value comparable to that measured for organic materials. The uranium oxide particle application demonstrates the high lateral resolution isotopic imaging capabilities of EUV TOF, although for precise measurements of isotope quantities the detection scheme will require modification.

Overall, EUV TOF is a new sensitive, high-resolution technique for elemental trace analysis with comparable performance to SIMS. This coupled with EUV TOF capability to map elemental composition at the nanoscale has potential to impact applications in the fields of nuclear forensic, chemical and environmental analysis.

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