Status of the Liquid-Xenon-Jet Laser-Plasma EUV Source

Innolite AB

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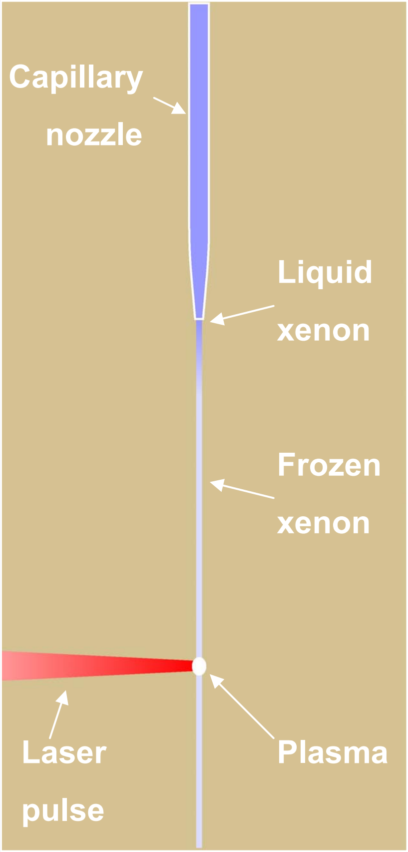
Core Technology
Xenon Liquid Jet / Filament LPP



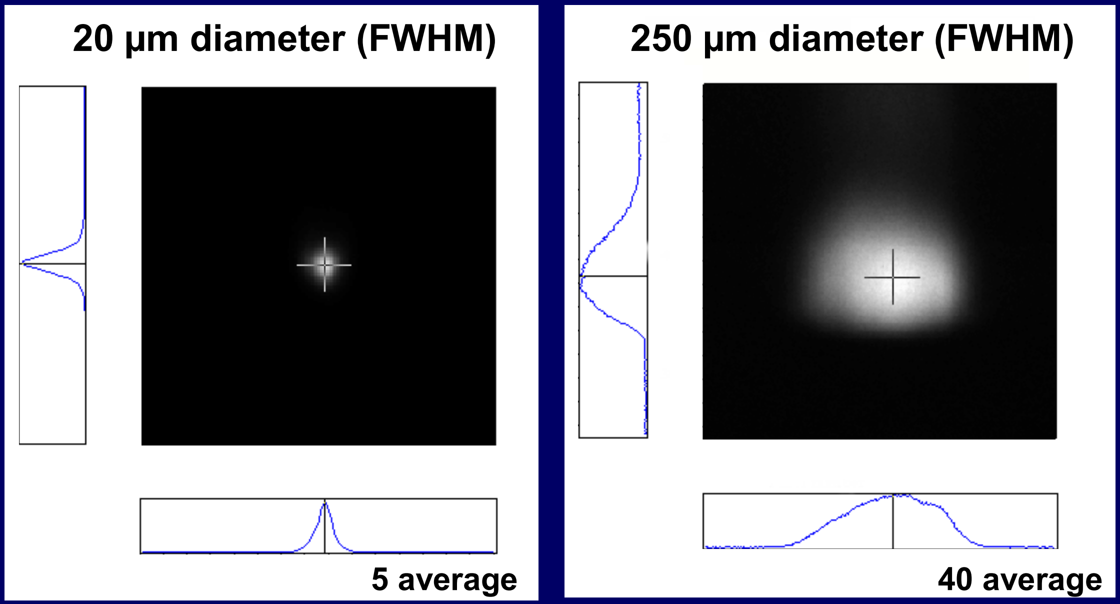
- Covered by general liquid-jet patent (6.002.744)
- Laser pulses are focused onto a highly stable xenon jet/filament
- Large working distance (>50 mm) limits thermal load on source mechanics.
- Free-standing plasma allows for large collection angles.

Performance Overview

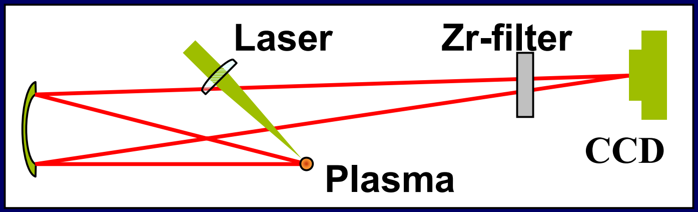
Conversion efficiency	0.95%
In-band power	0.5 W (50 W laser)
Maximum repetition rate	> 17 kHz
Plasma diameter	Scalable, 20 - 250 µm
Spatial stability	3 µm (1σ) shot-to-shot of 20 µm plasma
Spatial characterization	< 30% variation over ~120º
Out-of-band radiation	DUV = 1-3 % of EUV at wafer
Thermal-load capability	10-40 kW
Lifetime characterization	Sputtering from energetic ions identified. Mitigation schemes under evaluation.

Scalable Source Size

EUV plasma images



EUV camera



- 5 x Magnification
- Based on a spherical multilayer mirror
- Resolution < 10 µm @ 13.5 nm

- The source size is continuously scalable from 20 µm to 250 µm diameter.
- The smallest plasma gives very high brightness ($7*10^7$ W/m^2/sr with a 100 W laser) and is suitable for metrology/inspection systems.
- The larger plasma results in larger etendue better suitable for a stepper source.

High-Brightness Source

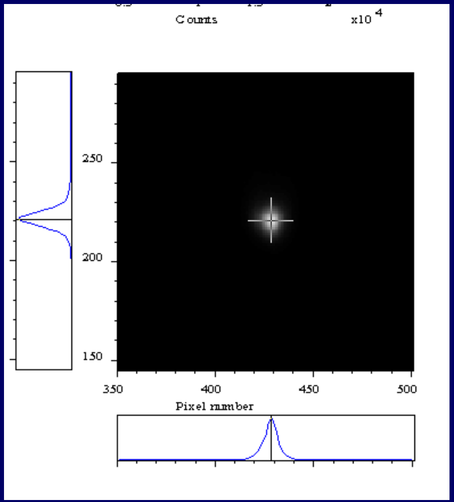
Current focus is the development of a low-power / high-brightness source for metrology and inspection (e.g. Aerial Image Microscope)

- Small source sizes gives high brightness with low total power
  - Commercial lasers (<100 W) can be used
  - Low total power limits thermal load
- The core target system can be reused in future high power system
  - Significant improvements of target system last six months
- Mirror lifetime will benefit from low total power
  - High repetition rate and low laser pulse energy limits ion energies, but sputtering issue still needs to be solved

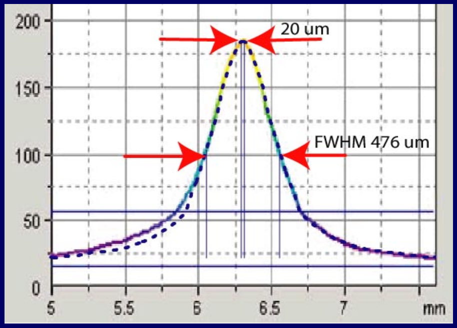
Comparison of Small and Large Plasma

	Liquid-Xenon-Jet LPP *		Typical GDP **	
Source FWHM	20 µm		476 µm	
Assumed CE	0.32% ***		0.6 %	
Peak Brightness	10^8 W/m²/sr	10^9 W/m²/sr	10^8 W/m²/sr	10^9 W/m²/sr
Total EUV power needed (into 2π)	0.5 W	5 W	240 W	2400 W
Total drive power needed	150 W	1500 W	40 kW	400 kW

*** Based on measured CE and source image.**



**** Based on published GDP data.**

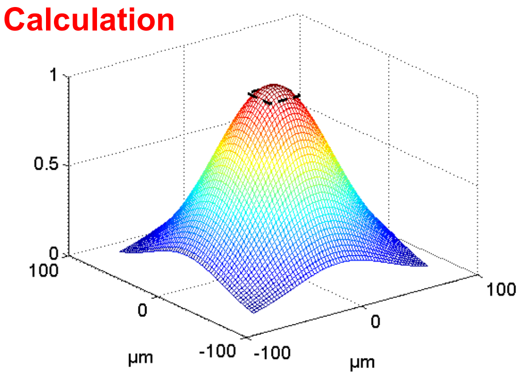


***** The CE of a very small plasma is typically smaller than the 0.95% of an optimal plasma. However, to achieve high brightness, the small plasma is still superior.**

High Emission Uniformity

By modifying the source shape, high emission uniformity (more top-hat) can be achieved over a large area while minimizing the total power needed.

Example: Goal is +/- 5% emission uniformity over 26x26 µm square



Gaussian source

Uniformity within 26x26 µm:

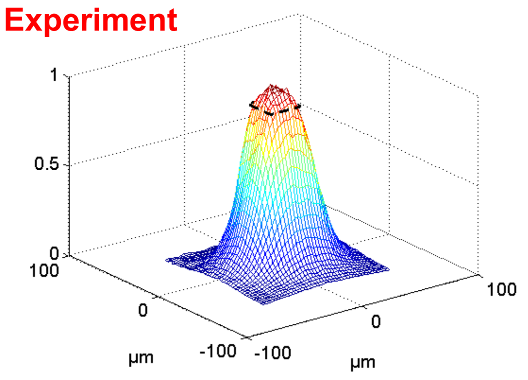
+/- 5%

FWHM:

96 µm

Power within 26x26 µm:

6,7% of total



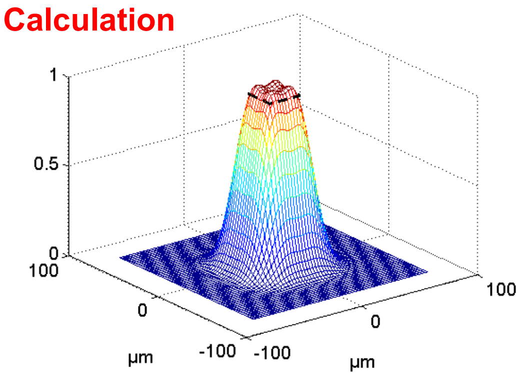
First Experimental result

Uniformity within 26x26 µm:

+/- 8%

Power within 26x26 µm:

22.5% of total



Modified source

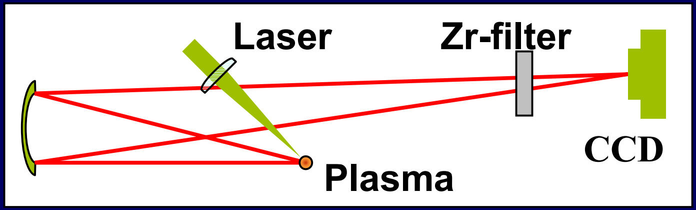
Uniformity within 26x26 µm:

+/- 5%

Power within 26x26 µm:

29,55 % of total

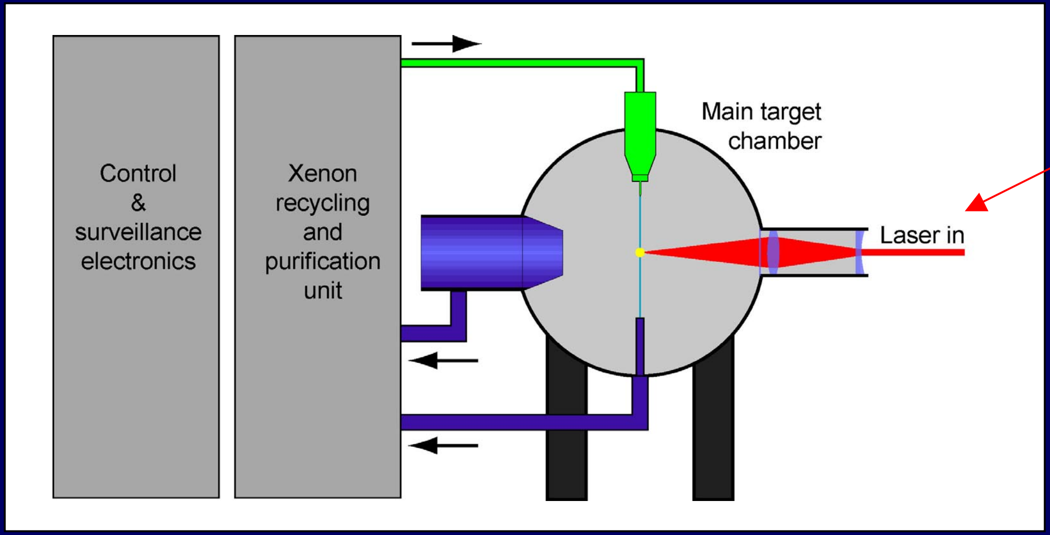
Emission distribution measured with EUV camera



Current Source Prototype

Core target system

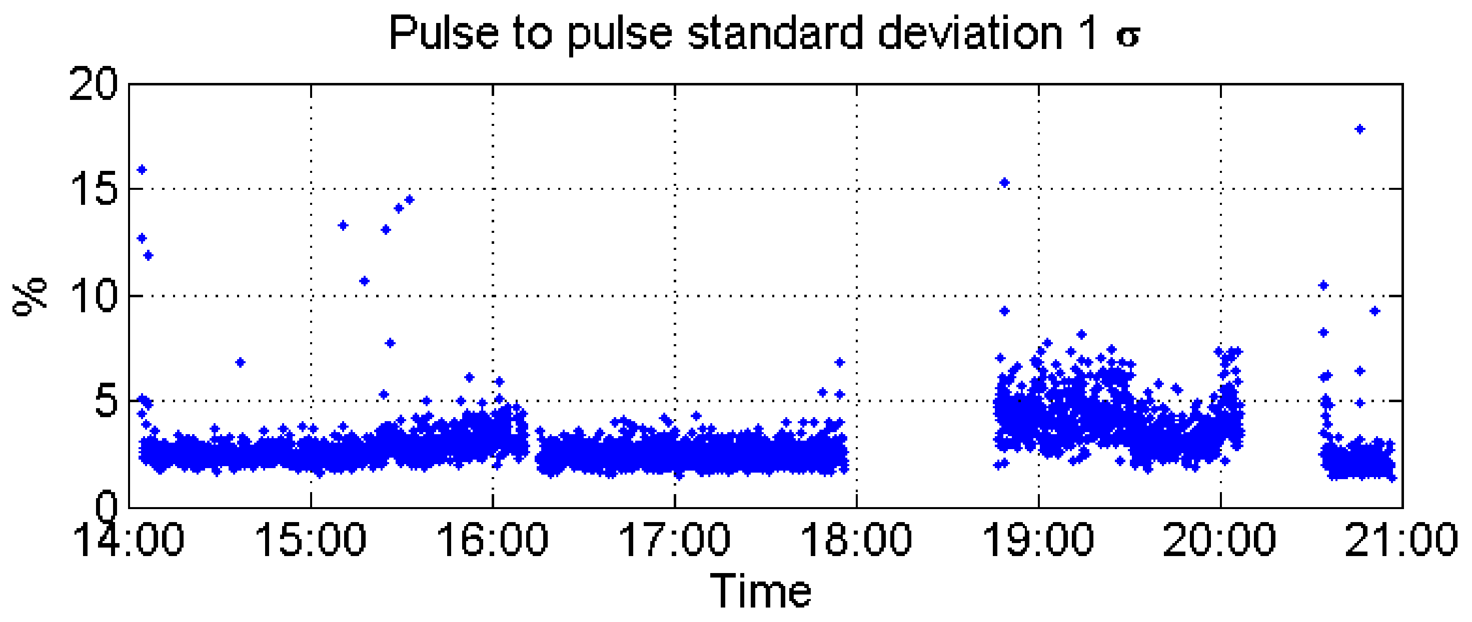
- 100% recycling of xenon with purification to PPB levels
- 8h continuous operation
  - Upgrade to fully continuous system is designed
- Automatic laser alignment
- ~10^-8 mbar base pressure



The target system is currently evaluated with a 50 W laser. This power is close to the requirements for a metrology/inspection unit, but M2 is too high and the repetition-rate is too low.

Long Term Stability Performance

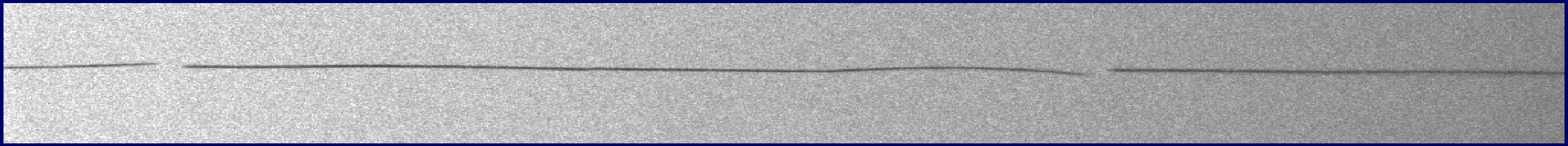
We have recently begun long term ‘hands-off’ testing of the source system. The following plot shows the stability of a typical 7 hour operation with some breaks. The average stability is 2.9% (1σ).



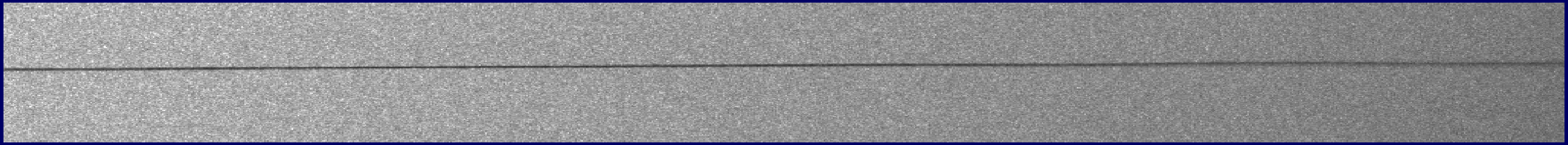
Jet Stability Improvement

Breakups were previously present in the xenon jet rusulting in occasionally missed pulses. This has now been solved.

Previous jets

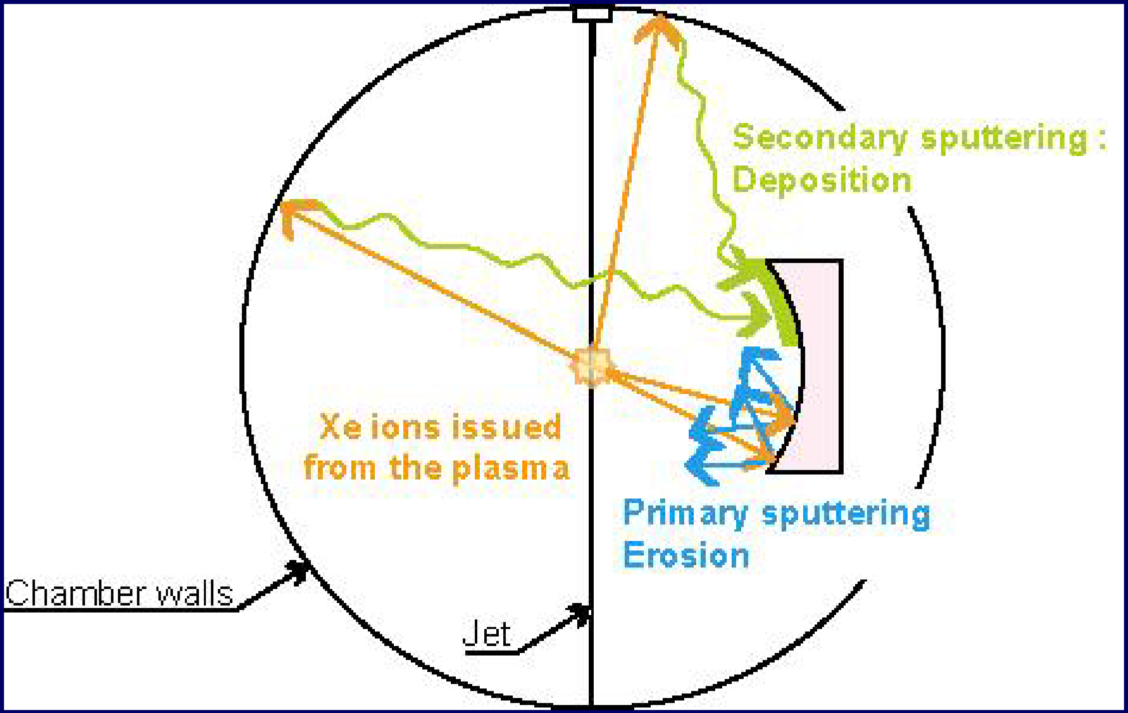


Current jets



Collector Lifetime – Sputtering Main Concern

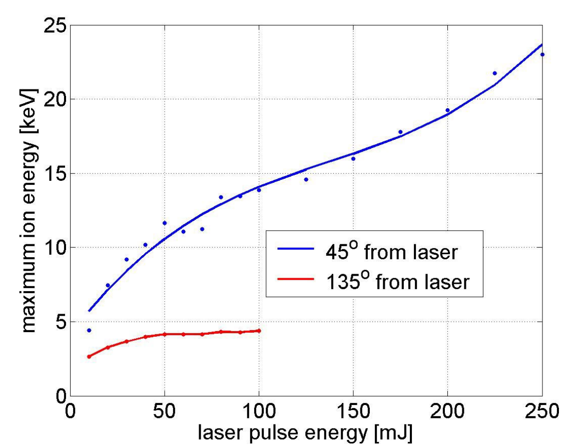
- Xenon is an inert gas, i.e. the evaporated target material is harmless *if not energetic*
- However, energetic ions and neutrals lead to primary and secondary sputtering and need to be slowed down



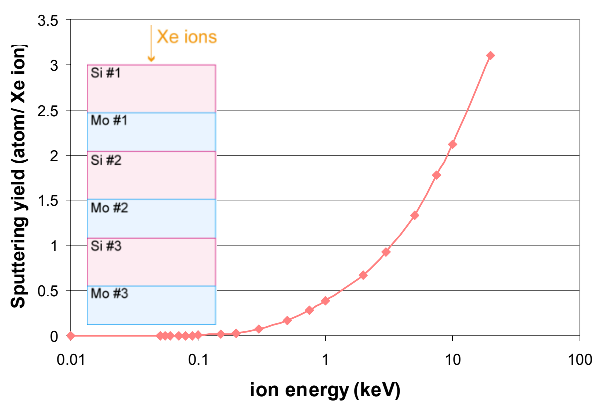
Ion Energies and Sputter Yield

- Even at low laser pulse energies typical for a metrology / inspection source (~20 mJ), ions in the multi keV range are ejected from the plasma.
- Calculations show that the sputtering yield of ions in the keV range is around unity.

TOF measurements of maximum ion energies



Si/Mo sputtering yield calculated at normal incidence with the SRIM code (TRIM calculations).



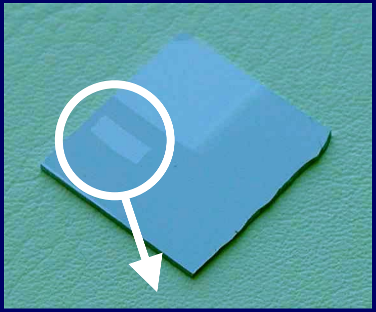
Sputtering Experiment

A silicon wafer was exposed to 10^6 pulses with 250 mJ pulse energy at 30 mm working distance.

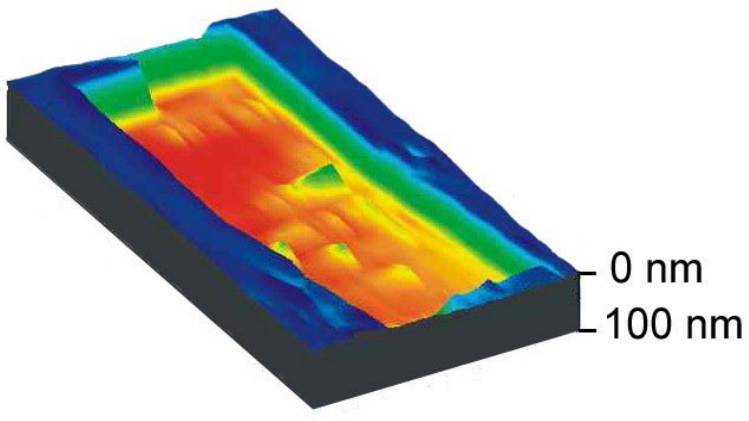
The edges between masked and unmasked areas were investigated with a KLA Tencor P-15 surface profiler

The unmasked area shows 100 nm sputtering

Exposed silicon wafer



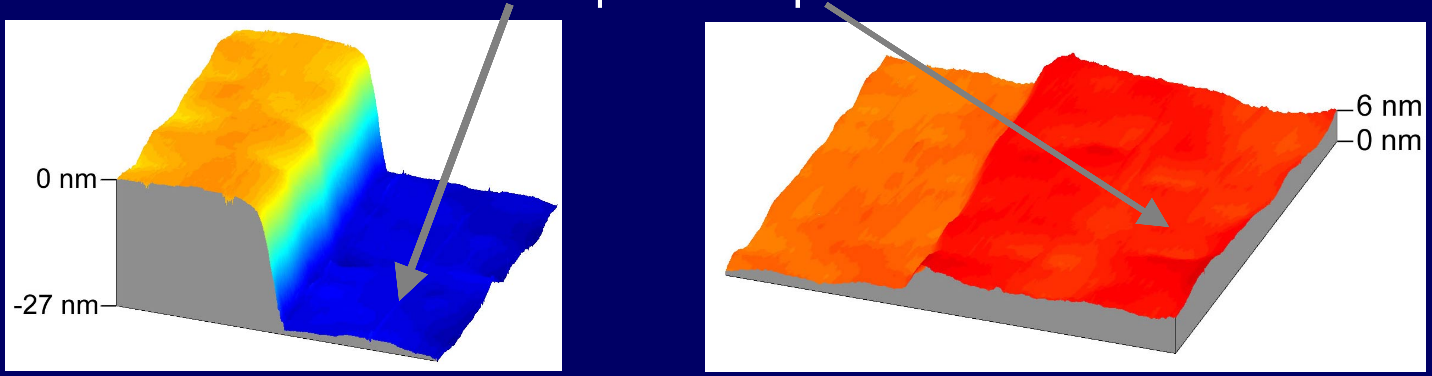
Surface profile



Gas Buffer Mitigation

- Mitigation by a gas background is promising to slow down ions to under the sputter threshold of ~150 eV
  - Calculations show that 1.2 10^{-2} mbar Ar stops 7 keV Xe ions while only absorbing 4% EUV per meter
- Experiments were performed with 10^6 pulses, 333 mJ pulse energy, 110 mm working distance – with and without an increased xenon background
- Depth profile of exposed area show that the increased xenon pressure lead to a small deposition (possible carbon growth) instead of sputtering

area exposed to plasma



Without buffer gas

With buffer gas

Alternative Target Materials

Preliminary data by P. Jansson et al, Royal Institute of Technology

- Xe EUV spectrum poorly matched to Mo/Si reflectivity curve, alternative target material could greatly improve CE.
- Sn has been discussed due to its spectral matching and similar Z.
- Initial experiments conducted on a 75 μm Sn/Pb solder jet
  - Debris deposition 300 nm after 5×10^4 pulses ($\sim 10^{-7}$ g/sr/pulse) at 72 mm from plasma.
  - Stepper source would require $>10^8$ debris mitigation. (10% loss, 1 year, 11 cm collector distance, 10 kHz)

Summary

- Innolite have continued to focus on the development of a low-power, high-brightness source for metrology/inspection purposes.
- It has been shown that a source with more top-hat emission distribution can be achieved.
- The core target system, that can be reused in future high-power sources, has been improved for better stability and reliability.
- Early mirror-sputtering experiments confirm sputtering from energetic xenon atoms but also indicates that a buffer gas can mitigate this sputtering.
- Experiment on liquid-tin target indicates high debris deposition. Xenon continues to be target of choice.

This presentation would not have been possible without all the hard-working people at Innolite...