Effect of Deposition, Sputtering, and Evaporation of Lithium Debris Buildup on EUV Optics

http://starfire.ne.uiuc.edu

M.J. Neumann[1], M.C. Cruce[1], P.R. Brown[1], D.N. Ruzic[1], O. Khodykin[2], N. Bowering[2]

[1]Department of Nuclear, Plasma, and Radiological Engineering

University of Illinois at Urbana-Champaign. Correspondence to druzic@uiuc.edu

[2] CYMER Inc., San Diego, California.

Abstract

One of the critical issues within EUVL is mirror lifetime and the degradation due to debris from the EUV pinch. This research modeled and experimentally measured the mitigation of Li debris from collecting on the surface of EUV-like optics through the combined use of a He secondary plasma, evaporation from optic materials at elevated temperatures, and preferential sputtering off of the optic material. Helium was chosen as the secondary plasma because of its high EUV transmission, 98%, at 13.5 nm and a preferential sputtering yield for lithium over mirror materials at low energies. This applied research expanded the current knowledge base in understanding lithium interactions with a He plasma and optic surfaces by constructing an experimental device that demonstrated that the application of a secondary plasma source around the surface of mirror optics contaminated with low-energy sputtered material was able to remove a significant fraction of lithium and contaminant material is removed. Concurrently, an analytical model was developed to give predictive values of contamination buildup on mirror optics for other related systems. The helium plasma had a temperature of 4.7 ± .5 eV and an electron density of 1 x 10^{-10} cm^{-3}. Ion flux to the mirror optic sample was on the order of 10^{17} He ions/sec. While the addition of heating the mirror optic to 400° C alone and the addition of He ion flux to the surface alone showed some promise in removal of Li debris from the surface of the optic the resulting surface roughness were on the order of 25-60 nm while the as received mirror optic sample had an as received surface roughness of 2.9 ± .5 nm. However, with the addition of heat and increased He ion flux to the surface together, this resulted in mirror surface having less surface roughness, 1.0 ± .5 nm and a minimal amount of Li debris present on the surface. This work demonstrates the viability of employing a secondary He plasma around the mirror optics to prolong the lifetime of the collector optics in situ with minimal EUV transmission loss.

Motivation for Li

•Debris from the plasma source is the critical issue.

•Fast ions generated in the pinch can lead to significant collector erosion.

•Electrode materials generated during the plasma pinch from surrounding surfaces and coat the mirror optics

•Condensable Li vapor can coat the mirror optics.

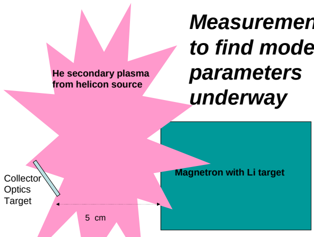
•Chemical interactions between collector mirror and debris can lead to mirror degradation.

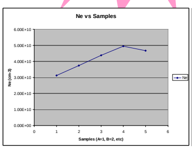
•Mirror temperature elevation can lead to enhanced thermal interdiffusion of the high and low index materials within the mirror structure.

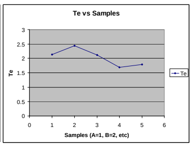
Source target element	Source element mass, amu	Maximum ion energy, eV	Peak ion energy, eV
Xe, 1064nm	131	20,000	10,000
Sn, 1064nm	119	6,500	2,450
Sn, 355nm	119	5,600	1,550
Li, 1064nm	7	1,200	550
Li, 355 nm	7	1,100	500

Ion Energy information from: From I. Fomenkov (CYMER), EUVL Source Workshop 2004*

Measurements to find model parameters underway







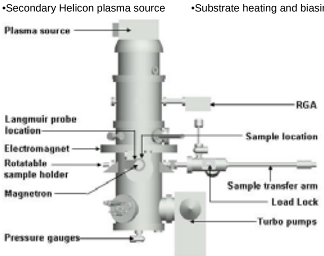
3000W, 80mT He plasma

(0.5 eV error in T_e, 1e10 error in n_e)

*S*urface *C*leaning of *O*ptics by *P*lasma *E*xposure

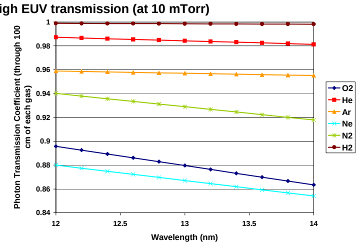
•Multifunctional device capable of creating lithium debris conditions incident upon EUV optic materials so as to develop a model of lithium transport and operating regimes that will aid in the advancement of EUV mirror lifetime optics.

•Lithium magnetron
•Secondary Helicon plasma source
•RGA
•Substrate heating and biasing



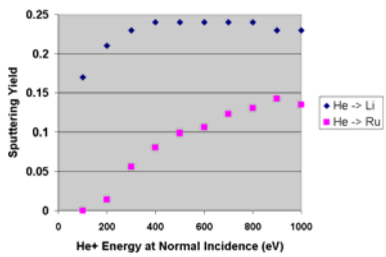
Why He as the secondary plasma?

•**High EUV transmission (at 10 mTorr)**



Modeling based off of Henke, B.L., E.M. Gullikson, and J.C. Davis, *X-Ray Interactions: Photoabsorption, Scattering, Transmission, and Reflection at E=50-30,000 eV, Z=1-92.* Atomic Data and Nuclear Data Tables, 1993. **54**(2): p. 181-342.

•**Preferential sputtering of Li over EUV mirror optic capping materials**



Modeling based off of SRIM.

Preliminary Investigation

Initial experiments with the use of secondary He plasma were performed to study the mitigation and removal of Lithium debris from mirror optics and the correlation to the initial model.

	He background pressure	Bias Voltage of MLM	Magnetron Plasma	Helicon Plasma	MLM Temperature
Sample 1	78 mT	0	Yes	No	50 C
Sample 2	78 mT	-100	Yes	No	50 C
Sample 3	78 mT	-100	Yes	Yes	50 C
Sample 4	78 mT	0	Yes	No	400 C
Sample 5	78 mT	-100	Yes	Yes	400 C

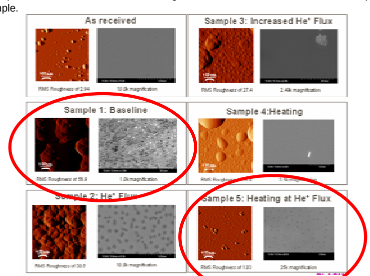
•Sample 1 s the baseline case.

•Sample 2 illustrates the effect of He^+ flux onto the mirror optic sample.

•Sample 3 illustrates the effect of increased He^+ flux onto the mirror sample

•Sample 4 illustrates the effects of heating alone.

•Sample 5 illustrates the effects of heating and additional He^+ flux onto the mirror optic sample.



Solution to an industry problem: This illustrates that the use of a secondary He plasma demonstrates possible in situ EUV optics cleaning!

More modeling and predictive nature needs to be determined, though, both for academia and industry.

Initial Model Development

Lithium debris at the surface of the mirror optic is governed by three competing processes:

$$R_{Net} = R_{Dep} - R_{Sput} - R_{Evap}$$

R_{Dep} : Deposition rate of Li debris on the mirror optic surface from the magnetron [m/s]

R_{Sput} : Sputtering rate of Li debris off of the mirror optic surface [m/s]

R_{Evap} : Evaporation rate of Li debris off of the mirror optic surface [m/s]

R_{Net} : Net deposition rate on the mirror optic surface [m/s]

$$R_{Dep} = \phi_{Mag}\{r,\theta\} A_{Sample} G_{Li}$$

where:

$$\phi_{Mag}\{r,\theta\} = \frac{I_{Mag}\cos\{\theta\}}{\pi r^2}$$

$$I_{Mag} = \Gamma_{He^+\to Li} Y_{He^+\to Li}\{E_{He^+}\} A_{Mag}$$

$$\Gamma_{He^+\to Li} = n_{He^+} \upsilon_{He^+} \qquad G_{Li} = \frac{1}{N_A} MW_{Li} \frac{1}{\rho_{Li}} \frac{1}{A_{Sample}}$$

$$R_{Sput} = \Gamma_{SampleHe^+} Y_{He^+\to Li}\{E_{He^+}\} A_{Sample} G_{Li}$$

$$\Gamma_{SampleHe^+} = n_{SampleHe^+} \upsilon_{SampleHe^+}$$

$$R_{Evap} = J_{LiEvap} A_{Sample} G_{Li}$$

$$J_{LiEvap} = \frac{P_{Li}}{kT_{Li}} \frac{\sqrt{\frac{8kT_{Li}}{\pi m_{Li}}}}{4}$$

Initial Model Analysis

- Sample 1:
  - Mirror sample was kept at 50° C.
  - 0V bias.
  - Magnetron plasma was exposed to the sample.
- R_{Evap} = 0 at this temperature.
- R_{Sput} = 0 because based off of initial I-V measurements, this is in the electron saturation region.
- From initial model, $R_{Net} = R_{Dep}$
- The current and voltage of the magnetron were measured so as to calculate a theoretical R_{Dep}
- Resulting film thickness was measured to give the experimental value of R_{Dep}

$R_{DepTheoretical}$	$R_{DepExperimental}$
18.33 nm/min	3.33 nm/min

- Sample 2:
  - Mirror sample was kept at 50° C.
  - **-100V bias to draw in He+ current to the mirror optic surface.**
  - Magnetron plasma was exposed to the sample.
- $R_{DepTheoretical}$ = 18.33 nm/min and $R_{DepExperimental}$ = 3.33 nm/min based off of sample 1.
- R_{Sput} is determined by knowing the voltage and current on the sample. This affords a calculation of $R_{SputTheoretical}$
- Resulting film thickness was measured to give the experimental value of $R_{NetExperimental}$ and from this, $R_{SputExperimental}$ was determined.

$R_{SputTheoretical}$	$R_{SputExperimental}$
7 nm/min	2.33 nm/min

- Sample 3:
  - Mirror sample was kept at 50° C.
  - -100V bias to draw in He+ current to the mirror optic surface.
  - Magnetron plasma was exposed to the sample.
  - **Addition of secondary He plasma to increase He+ flux to mirror optic surface.**
- $R_{DepTheoretical}$ = 18.33 nm/min and $R_{DepExperimental}$ = 3.33 nm/min based off of sample 1.
- R_{Sput} is determined by knowing the voltage and current on the sample. This affords a calculation of $R_{SputTheoretical}$
- Resulting film thickness was measured to give the experimental value of $R_{NetExperimental}$ and from this, $R_{SputExperimental}$ was determined.

$R_{SputTheoretical}$	$R_{SputExperimental}$
7.9 nm/min	<3.33 nm/min

- Sample 4:
  - **Mirror sample was kept at 400° C.**
  - 0V bias.
  - Magnetron plasma was exposed to the sample.
- $R_{DepTheoretical}$ = 18.33 nm/min and $R_{DepExperimental}$ = 3.33 nm/min based off of sample 1.
- R_{Sput} = 0 because no He+ ions are being drawn to the mirror surface.
- Knowing the temperature of the sample afforded for the calculation of $R_{EvapTheoretical}$
- Resulting film thickness was measured to give the experimental value of R_{Net} and from this, $R_{EvapExperimental}$ was determined.

$R_{EvapTheoretical}$	$R_{EvapExperimental}$
5180 nm/min	3 nm/min

- Sample 5:
  - Mirror sample was kept at 400° C.
  - **-100V bias to draw in He+ current to the mirror optic surface.**
  - Magnetron plasma was exposed to the sample.
  - **Addition of secondary He plasma to increase He+ flux to mirror optic surface.**
- $R_{DepTheoretical}$ = 18.33 nm/min and $R_{DepExperimental}$ = 3.33 nm/min based off of sample 1.
- $R_{SputTheoretical}$ = 7.9 nm/min and $R_{SputExperimental}$ = 2.33 nm/min based off of sample 3.
- $R_{EvapTheoretical}$ remains the same as in sample 4.
- There was no discernable $R_{NetExperimental}$. However, this is not due to the evaporation flux as this the exact same experiment as for sample 4, but the only difference is the enhanced He+ flux to the mirror surface.

So, there needs to be a model adjustment!

Model Adjustment

- Initial assumption that Li was sputter as neutrals alone.
  - Sputtered Li ions are deposited on magnetron because of sheath potential.

$$I_{Mag} = \Gamma_{He^+\to Li} Y_{He^+\to Li}\{E_{He^+}\} f A_{Mag}$$

- Li debris is being mitigated by He plasma from magnetron.
  - Scattering by background gas.

$$J_{Sample}\{r,\theta\} = -D_{Li\to He} \nabla \phi_{Mag}\{r,\theta\}$$

  - Ionization be electrons in plasma.

$$L^2 = \frac{D_{Li\to He}}{\Sigma_{IZ}\{E_{He^+}\}}$$

$$\phi_{Mag}\{r,\theta\} = \frac{I_{Mag}\{r,\theta\} e^{-r/L}}{D_{Li\to He}\, \pi r}$$

- The definition of the evaporative flux must be redefined to account for the presence of multiple species present of the mirror optic surface.
  - The evaporative flux is should be though of as being a sum total of the evaporative flux from the various composition species present on the mirror optic surface.
- The definition of the evaporative flux must be redefined to account for the additional energy present at the surface of the mirror optic from the He+ flux that is incident on the mirror optic.
  - When He+ ions are incident on the mirror, through momentum transfer, there is a deposition of energy on the mirror surface.
- Sample 4 indicated that it is not pure Li debris on the surface on the mirror optic, but that there were other contaminants that will be sputtered at different rates based on their percentage composition.

$$R_{Sput} = \Gamma_{SampleHe^+}[\theta_{Li} f_{He^+\to Li} Y_{He^+\to Li}\{E_{He^+}\} G_{Li} + \theta_O f_{He^+\to O} Y_{He^+\to O}\{E_{He^+}\} G_O + \ldots] A_{Sample}$$

- There exists the potential for a temperature dependence on the sputtering yield of each species on the mirror optic that could come into play as the thermal transfer of energy to the mirror optic contributes to the total energy that is deposited at the surface.

$$Y_X = \Lambda_X F_D\{T_{Li}\}$$

Λ_X : Material parameter specific to each 'x' material. [1/m]

$F_D\{T_{Li}\}$: Energy present at the surface from ion bombardment and thermal energy [J/m]

$$J_{Evap}\{\Delta T_{He^+ Flux}\{\Gamma_{He^+\to Surface}\}\} =$$

$$\theta_{Li}\{\Gamma_{He^+\to Li}, E_{He^+}\}\left(\frac{P_{Li}\{T_{Li} + \Delta T_{He^+ Flux}\{\Gamma_{He^+\to Surface}\}\}}{k(T_{Li} + \Delta T_{He^+ Flux}\{\Gamma_{He^+\to Surface}\})} \frac{\sqrt{\frac{8k(T_{Li} + \Delta T_{He^+ Flux}\{\Gamma_{He^+\to Surface}\})}{\pi m_{Li}}}}{4}\right) +$$

$$\theta_{Li_2O}\{\Gamma_{He^+\to Li}, E_{He^+}\}\left(\frac{P_{Li_2O}\{T_{Li} + \Delta T_{He^+ Flux}\{\Gamma_{He^+\to Surface}\}\}}{k(T_{Li} + \Delta T_{He^+ Flux}\{\Gamma_{He^+\to Surface}\})} \frac{\sqrt{\frac{8k(T_{Li} + \Delta T_{He^+ Flux}\{\Gamma_{He^+\to Surface}\})}{\pi m_{Li}}}}{4}\right) + \ldots$$

$P_X\{T\}$: Vapor pressure of 'x' species as a function of that species temperature, which is in thermal equilibrium with that T_{Li} and the additional energy that comes from He+ flux interaction.

$\Delta T_{He^+ Flux}\{\Gamma_{He^+\to Surface}\}$: Increased temperature of the mirror optic surface due to He+ flux bombardment

Future Work

- 1: Determination of R_{Dep}
- 2: Diffusion, Ionization, and Scattering: Vary plasma power, pressure. Measuring T_e and n_e will determine L^2 and D or others parameters needed for further model development.
- 3: Sputtering of mirror optics: Vary sample T. Measure TOF-SIMS spectra for determination of composition.
  - 3a: Debris composition with regards to sample T: Profiling with TOF-SIMS.
  - 3b: Temperature dependent sputtering for determination of R_{Sput}
- 4: Vary O partial pressure and mirror optic T. Measure R_{Net} for determination of θ ratio.
- 5: Determination of J_{Evap} in relation to Γ_{He+} and energy: Vary Γ_{He+} and E to sample, vary sample T. Measure R_{Net}. Determine θ and ΔT dependence on Γ_{He+} and E.
  - 5a: Holding E_{He+} below the sputtering threshold.
  - 5b: Determining θ and J_{Evap} dependence on E_{He+}

Acknowledgements

This work was supported by CYMER Corporation under contract, Oleg Khodykin, Mgr., and INTEL Corporation under contract SRA 159-03, Robert Bristol Mgr. Special thanks to Alex Ershov, Norbert Bowering, Oleg Khodykin, Oscar Hemberg, and Bill Marx at CYMER Inc.

Thanks to the Center for Microanalysis of Materials supported by US DOE DEFG02-91-ER45439.