Protection of Collector Optics in an LPP Based EUV Source

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ABSTRACT

In a laser produced plasma (LPP) EUV source the multilayer mirror (MLM) collector optic will be exposed to a flux of energetic ions and neutral atoms ejected from the plasma as well as condensable vapor from excess target material. We are investigating various techniques for reducing the contamination flux and for in-situ removal of the contamination. The protection strategies under investigation must be compatible with gaseous and condensable target materials such as Xe, Sn, In, Li, and other elements. The goal is to develop MLM structures that can withstand elevated temperatures and develop protective barrier coatings that reduce erosion of the mirror surface. Results of MLM exposure to energetic ion beams and thermal atomic sources are presented. Changes in EUV reflectivity of MLM structures after exposure to ions and deposition of target material have been performed on samples cleaned by these developmental processes. In this paper, we will summarize our initial results in these areas and present techniques for mitigation of MLM damage from the source.

Keywords: EUV, Collector, Ion Bombardment, Multilayer Mirror, Mirror Lifetime, Lithium, Tin, Xenon, Optics Damage

1. INTRODUCTION

Debris from a laser-produced plasma (LPP) EUV light source damages optical surfaces that are in direct line-of-sight proximity. Since no material has been found for an EUV-compatible window, allowing the light to pass through weakly attenuated while stopping the debris flux, we must provide subsystems to (i) slowing down and stopping of fast moving material that can reach collector and cause its erosion, (ii) clean collector off of a slow moving condensable material that did reach the collector surface. For purposes of solving these issues, debris can be divided into at least two categories: (1) fast ions directly expelled from the LPP and (2) neutralized target material either from the active (emitting) plasma or excess material from the target delivery stream. Either of these debris may condense on the optics. The most significant problem caused by the debris is reduction of in-band reflectivity of the collector that must be in close proximity to the radiating LPP. For example, some designs call for the collector front surface to be held within 20-30 cm of the plasma.[1]

At Cymer, we are developing several approaches to mitigate the problems posed by debris material from the LPP. Several subsystems to slow down the fast moving debris are in various stages of development, and indeed may be eventually combined to gain very high suppression factors. Given that the power carried out by fast ions may be in a range of several kilowatts, simple power dissipation is a nontrivial issue. The debris slowing techniques may not completely prevent debris from reaching the collector surface at thermal speeds and depositing on it. This debris will be removed by one or more other methods, dependent on the chemical properties of the material. For a Li target, we propose to heat the mirror to a high temperature so that evaporation of Li from the MLM surface exceeds the rate of Li debris deposition. Various methods are also being developed to prevent Li from diffusing into the MLM structure and reducing its reflectivity.

2. CHARGED PARTICLE DEBRIS

2.1 Ion Characteristics

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The type of damage induced in a multi-layer reflector by fast ions and the extent of that damage depends on characteristics of the ions including particle mass, charge, and energy. For example, lighter ions (e.g. Li) will sputter mirror materials at a significantly lower rate than the same energy heavy ions such as Sn and Xe. Indeed, the significant erosion in the ETS collector mirror was attributed to sputtering by high energy Xe ions[2] that have a significantly higher sputter yield than Li. Furthermore, higher charged ions possess greater kinetic energy, so a low Z material such as Li, generally has lower energy per ion. Table 1 shows maximum ion energy and peak ion energy that we have measured for various laser conditions for Li and Sn targets.

Ion species	Laser parameters	Maximum ion energy (eV)	Peak ion energy (eV)
Li	355nm, 6ns	1100	600
	355nm, 1ns	2700	900
	1064nm, 6ns	1150	550
	1064nm, 1ns	3000	650
Sn	355nm, 9ns	5500	1550
	1064nm, 9ns	6500	2450

Table 1. Measured ion characteristics from planar LPP targets for various laser conditions.

A more detailed characterization of the ion flux was done using an array of Faraday Cup (FC) detectors equipped with biased repeller grids for more accurate measurement of the ion energy spectra. The detectors were arranged at various angles from a planar target to determine angular dependence of the ion flux relative to the laser propagation vector, nominally held at normal incidence.

Finally, FC measurements have also shown that the highest energy components are dominated by the higher charge state ions. Specifically, the energy spectrum for an ion population from a single LPP can be calculated by time-of-flight (TOF) analysis. However, when a repeller grid at the entrance to the FC collector is biased to a given voltage, TOF analysis indicates that ions with energy *2* or *3* times the electron charge-bias voltage product (qV) are suppressed. These higher charge state ion components seem to dominate especially at large angles from the laser beam, probably as a result of the lower path-integrated density at high oblique angles from a planar target. This lower density allows higher charged ions to escape with lower probability of charge exchange or collisional recombination.

	Li (50um foil)			Sn (50um foil)		
	25-deg	50-deg	75-deg	25-deg	50-deg	75-deg
Normalized ion flux	1	0.25	0.17	1	0.41	0.12
Maximum kinetic energy (eV)	1150	650	450	5500	7800	20000

Table 2. Measured ion flux and maximum kinetic energy at various angles (relative to normal incidence). The flux is normalized to that measured at 25 degrees. Laser wavelength is 355nm.

2.2 Ion Mitigation

Several different methods are currently under investigation for preventing moderate energy ions from reaching the collector surface. Dissipating the energy carried by ions is an important issue for any proposed ion mitigation technique, because the power is so large. For example, in case of Li target material, it has been estimated that about 80% of the laser power is converted to kinetic energy of debris. For the laser power of 10 kW, expected for a production tool, that translates into 8 kW of the dissipated kinetic energy through this channel. The power partitioned into kinetic energy is less for a tin target, but is still substantial.

The effectiveness of one ion mitigation technique can be seen in Figure 1. The signal induced by ions collected in the Faraday Cup is shown as a function of time, following illumination of the laser on the target. When no ion mitigation is applied, a significant fast ion component with energies greater than 1-2 keV is present. The same conditions are repeated with the ion mitigation technique #1 applied. Note that the total flux and peak energy are both reduced significantly. The sputter yield projected from this flux is 8.5 times less due to a lower overall flux and about 2 times less due to a lower ion energy for a total sputter reduction of approximately 17 times.

A second technique has also shown significant promise for reduction of the ion flux as shown in the Figure 2. We estimate efficiency of this technique to be about 12 times.

The effectiveness of the third technique we are investigating is shown in Figure 3. Similar to technique #2, this technique primarily reduces the ion flux. We estimate its effectiveness to be about 19 times.

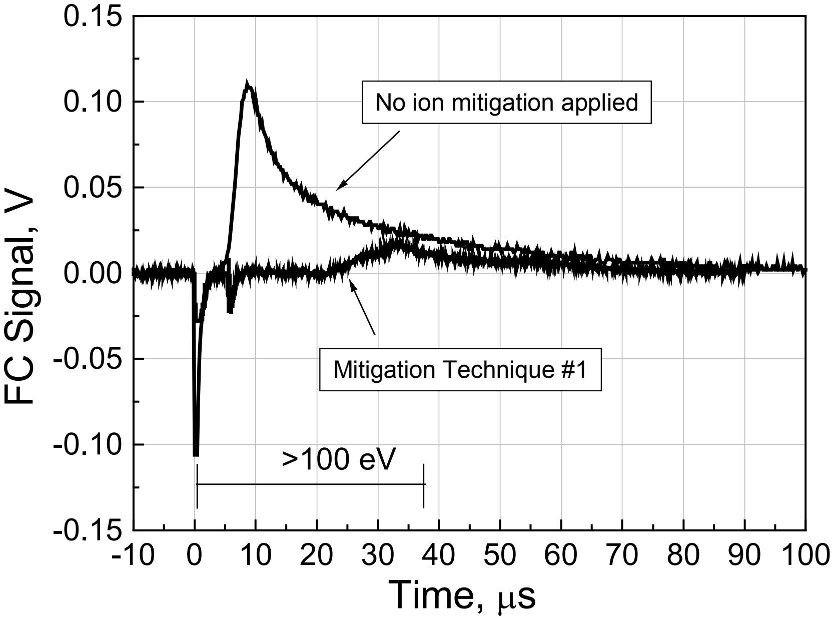

Figure 1. Faraday Cup signals associated with an LPP pulse with and without the mitigation technique applied. Note that when the technique is applied, both the total flux and the peak energy are reduced significantly

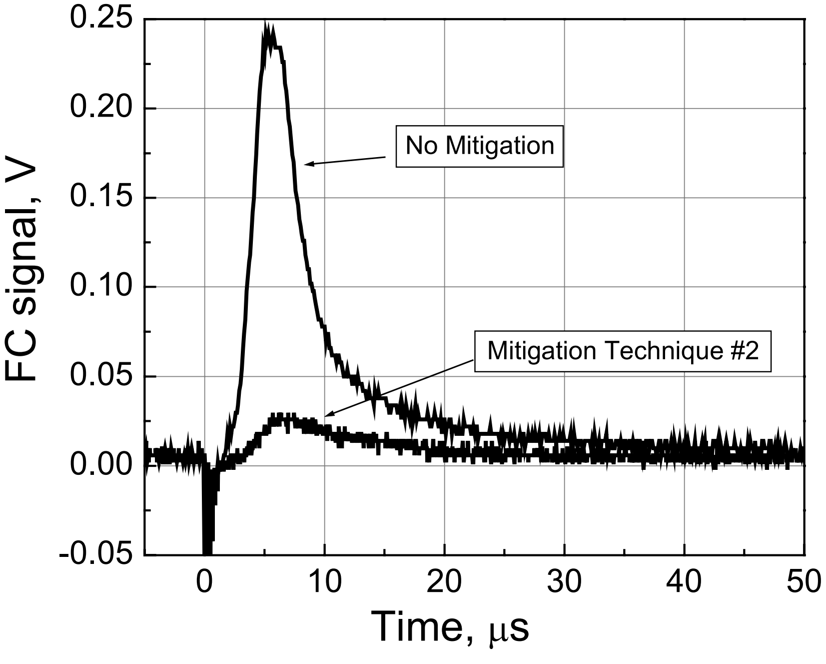

Figure 2. Signals from a Faraday cup viewing the LPP through the mitigation technique #2.

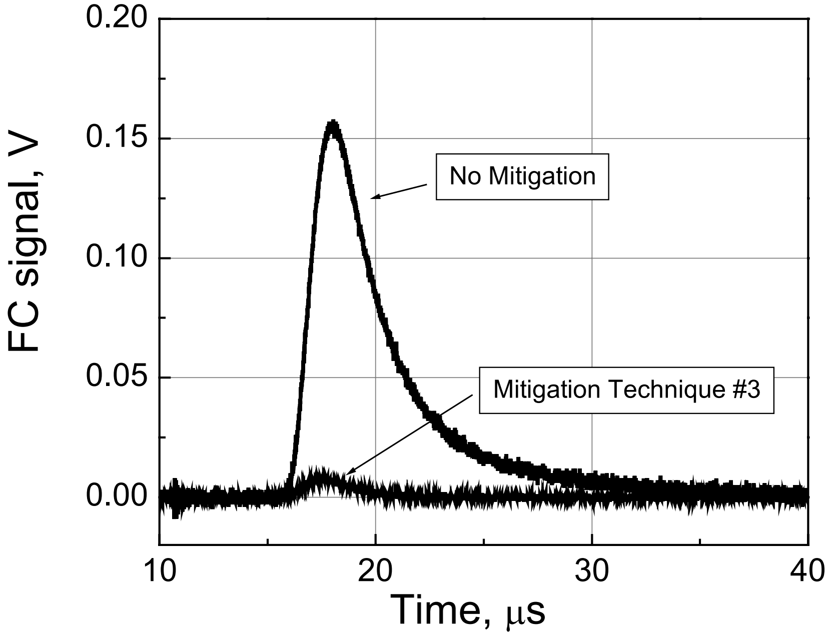

Figure 3. Signals from a Faraday cup viewing LPP through the mitigation technique #3.

Table 3 summarizes the estimated efficiencies of all three techniques. In our estimation we assume that 15M pulses cause erosion of 1 pair of the MLM, which was an estimated erosion rate for Xe ions at ETS. We assume to have about 20 sacrificial pairs on the MLM that can be sputtered off without reflectivity degradation. We also assume that because Li is a lighter ion there will be about 12X improvement in the lifetime due to lower sputter yields for Li. Calculations show, that under these assumptions just one technique with the lowest efficiency (12X) will be sufficient to achieve 45B pulses erosion-related MLM lifetime. The other two techniques provide a safety margin in case 15M pulses per an MLM pair estimation proves to be too optimistic.

	Estimated reduction of collector erosion
Technique #1	~17X
Technique #2	~12X
Technique #2	~19X

Table 3. Summary of ion slowing techniques efficiency.

3. REMOVAL OF TARGET MATERIAL FROM THE COLLECTOR

3.1 MLM Protection from Condensable Materials with a Li Target.

The technical path we are pursuing utilizes a Li target as an active emission element and a heated multi-layer mirror that provides for the evaporation cleaning of lithium material that did get deposited on the collector surface. An estimated temperature of about 400C will be required. Conventional MLM structures degrade rapidly at these temperatures due to thermally enhanced interdiffusion of the high and low index materials (esp. Si and Mo). Therefore, we have been actively developing alternative multi-layer mirror structures that display very high reflectivity and wavelength stability at these high temperatures. It should be noted that even when the MLM is heated to these temperatures, a thin but finite Li layer exists on the MLM surface. This Li, in the absence of further precaution, would easily diffuse into the MLM structure. Thus, we are also developing effective diffusion barriers to Li with suitably low EUV absorption.

3.1.1 High Temperature MLM Development

The research program at Cymer is aimed at the development of collector mirrors with multilayer coatings that can be operated at the temperatures up to 500 ºC. The reflectance of multilayer coatings based on molybdenum – silicon bilayers is known to degrade severely at elevated temperatures of more than 200 ºC due to the formation of molybdenum silicides at the layer interfaces[3]. However, other bilayer coatings like $MoSi_2/Si$ and also interface-engineered multi-layer systems have recently been developed and show promise to provide thermally stable collector mirror coatings with favorable optical properties at temperatures up to 500 ºC[4]. Such coatings can be employed on a heated mirror that relays the in-band EUV radiation to the intermediate focus point.

3.1.2 Li diffusion Barrier Development

Exposure of MLM to Li flux can lead to a rapid MLM degradation due to high diffusion rate of Li into MLM. To overcome this problem an MLM structure should utilize materials that can stop this Li diffusion. These materials should combine high EUV transparency, extremely low Li diffusion rate and compatibility with MLM structure. We have complied and tested over 15 different candidate materials. All these materials have been tested on an experimental setup shown in Figure 4. It consists of a holder for witness samples with two thermocouples attached to it, a radiative heater placed behind the holder and a Li effusion cell on a movable feedthrough. The samples were heated to 400C and exposed to lithium vapors from a Li effusion cell for 10minutes. After the exposure, samples were kept hot for 12 hours. Annealed samples were taken out of vacuum and analyzed using SIMS microscope (Millbrook Mark 2).

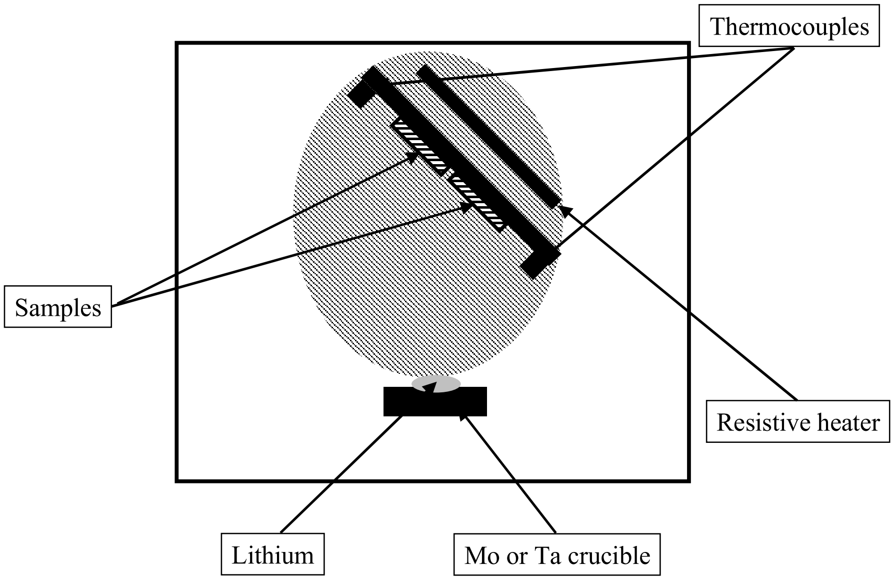

Figure 4. Experimental setup for testing lithium diffusion barriers.

Fig. 5 shows SIMS analysis of a Ru-capped MoSi2/Si MLM exposed to Li. Mirror sample was prepared by Sasa Bajt from LLNL. One can see that Li signal is detected all the way through both the capping layer and the MLM structure. The EUV reflectivity of this mirror after exposure to Li was practically zero.

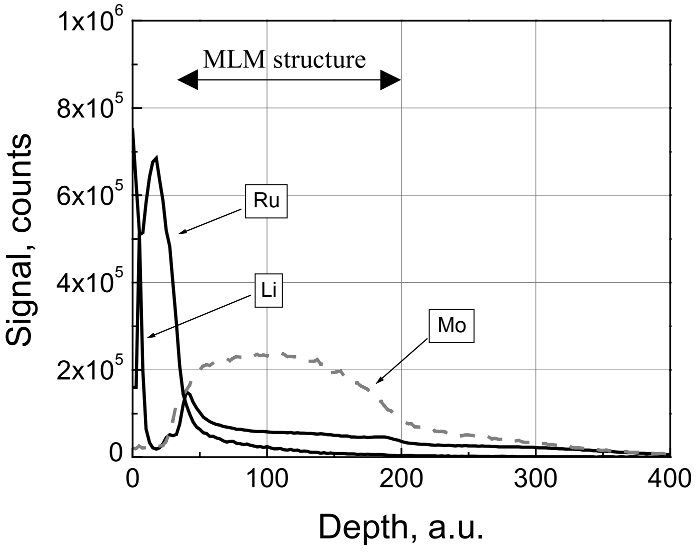

Figure 5. SIMS analysis of Ru-capped $MoSi_2$/Si MLM after exposure to Li.

After careful study of all the materials in our list, we have found two promising candidates. The SIMS profiles for the MLM's made with these materials are shown in Figs. 6 and 7.

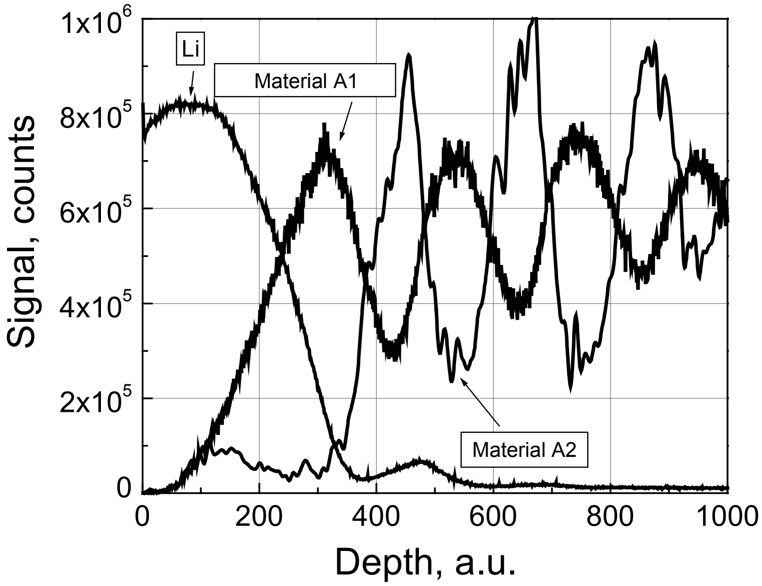

Figure 6. SIMS analysis of EUV MLM made with candidate material A after exposure to Li.

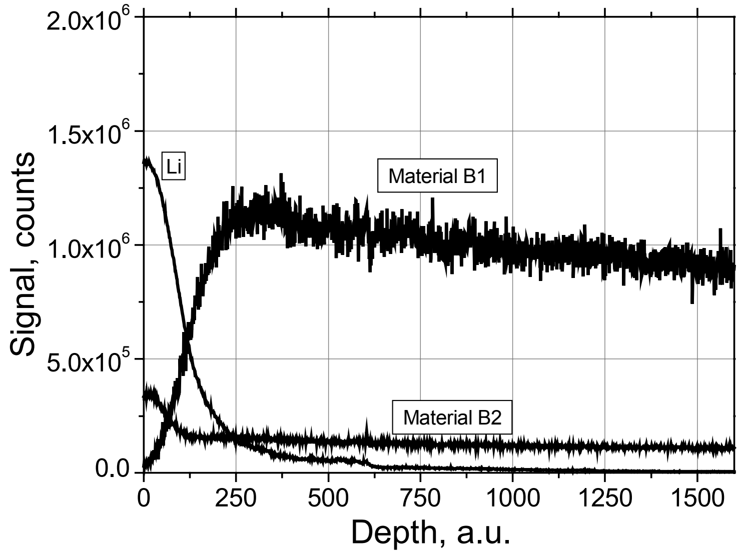

Figure 7. SIMS analysis of EUV MLM made with candidate material B after exposure to Li.

Note, that SIMS does not resolve the multiplayer structure of the candidate material B. However, the mirror does maintain its periodic structure and reflects EUV. Fig. 8 shows normalized EUV reflectivity of the MLM made with the candidate material B after exposure to Li.

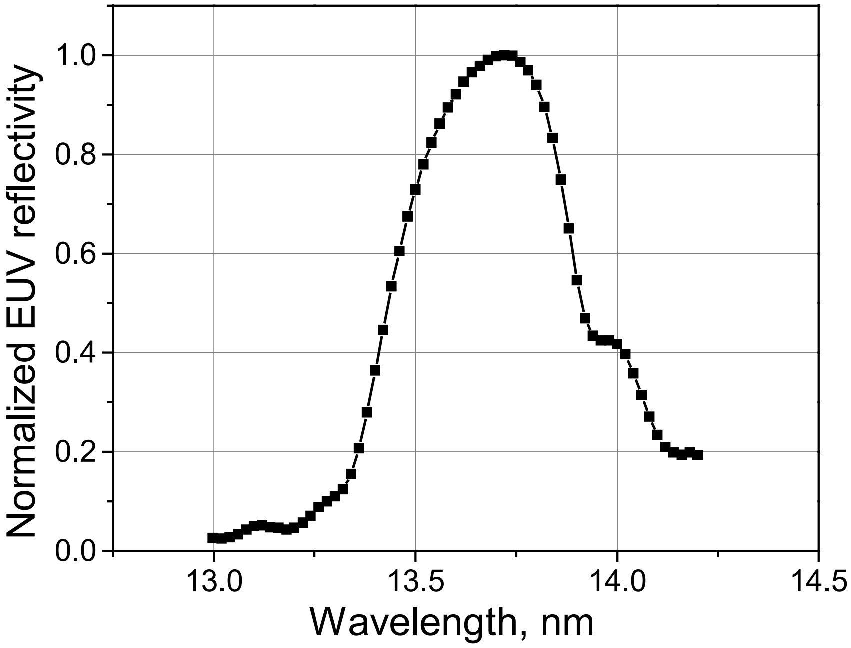

Figure 8. EUV reflectivity of MLM made with candidate material B after exposure to Li.

SUMMARY

While the problem of protecting the collector mirror in a LPP EUV source is the most important and challenging issue facing development of a HVM capable EUV light source, we are currently well along the development path of subsystems to mitigate the debris issue. The problem of fast ions from the target material is being addressed by at least three different mitigation techniques. Techniques for removal of condensable debris from the collector surface are underway as well. Our principle approach, utilizing a Li target, relies on the MLM being held at a temperature greater than the evaporation point of Li. The thin residual layer has negligible absorption and is prevented from diffusion into the MLM structure by a barrier material with low EUV absorption.

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