The Effect of Debris on Collector Optics, its Mitigation and Repair: Next-Step a Gaseous Sn EUV DPP Source

Brian E. Jurczyk*[a], Darren A. Alman[a], Erik L. Antonsen[a], Michael A. Jaworski[a], Michael J. Williams[a], David N. Ruzic[a], Timothy Spila[b], Ginger Edwards[c], Stefan Wurm[c], Obert Wood[c], Robert L. Bristol[d]

[a]Plasma-Material Interaction Group, Univ. of Illinois at Urbana-Champaign, Urbana, IL 61801
[b]Center for Microanalysis of Materials, University of Illinois at Urbana-Champaign, IL 61801
[c]SEMATECH, Austin, TX 78741
[d]Intel Components Research, Hillsboro, OR, 93751

ABSTRACT

The critical issue related to advanced fuel plasma EUV sources is collector lifetime. The Illinois Debris-mitigation EUV Applications Laboratory (IDEAL) is continuing research with a dense plasma focus (DPF) light source. The IDEAL DPF electrodes have been redesigned in order to allow for advanced fuel testing, better pinch operation and increased debris generation. The DPF light source operates at negative polarity, 50 Hz, 3 kV and 7.5 Joules of energy per pulse with tetramethyltin [(CH3)4Sn] as an advanced fuel source. EUV output power is measured with filtered photodiodes and results from a gridded energy analyzer still show two primary ion components with a high-energy peak near 6keV. A Faraday-shielded immersed RF antenna provides a 2kW secondary discharge near the DPF for both pre-ionization and mitigation of the debris with a foil trap (>90%). In addition the Surface Cleaning of Optics by Plasma Exposure (SCOPE) facility has been constructed where evaporated and/or ion implanted metals can be deposited on and removed from EUV mirrors. In SCOPE metals were evaporated on to mirror samples held at various temperatures. A metal ion beam was also added to simulate the energetic erosive flux and a helicon plasma was used in situ to study plasma cleaning. Reactive ion etching of tin by chlorine and other gases has shown 500:1 selectivity factors and very high etch rates suitable to refresh an optical mirror surface within a few seconds. Mirror samples were analyzed at the Center for Microanalysis of Material where the diffusion and transport of the metals and surface roughness were studied for lifetime estimation. Lastly, the Xtreme Characterization EUV Experiment Device (XCEED) was used for characterization of the debris has been accomplished by use of an energy sector analyzer in combination with ion time-of-flight. This diagnostic has been designed to measure velocity, mass and charge states of the incoming ions and neutrals, giving discrete debris spectra while in negative polarity operation. Latest results will be presented based on this work.

Keywords: EUV source, debris, optics, collector lifetime, mitigation, plasma cleaning, etching, debris spectra

1. INTRODUCTION

The semiconductor industry plans to move to the 13.5 nm wavelength of light for lithography of transistors in new computer chip manufacturing methods. One challenging problem in making EUV lithography a manufacturing technology is operation of a satisfactory light source in conjunction with collector optics required for light capture. There are currently two prospects for EUV light sources being considered. The first is a Laser Produced Plasma (LPP) which uses a pulsed laser to ablate a solid fuel source and create high temperatures required for EUV light generation. The second option is a Discharge Produced Plasma (DPP) which uses a gaseous z-pinch to compress plasmas to high temperatures generating the ion species required for EUV light emission. Both of these source options generate a significant amount of debris, such as energetic ions, that necessarily interacts with collector optics in the source chamber causing erosion and deposition of materials on the mirrors. Ultimately these debris mechanisms degrade mirror reflectivity, decoupling the light source from the rest of the manufacturing process.

Emerging Lithographic Technologies IX, edited by R. Scott Mackay,
Proceedings of SPIE Vol. 5751 (SPIE, Bellingham, WA, 2005)
0277-786X/05/$15 · doi: 10.1117/12.600048

The radiators which produce the desired 13.5 nm EUV light can come from high charge states of Xe or Sn. Xe-fueled sources have a lower efficiency for generating the desired wavelength (~ 1%) compared to Sn (~ 3.5%), but Sn-fueled sources have an additional debris component, the Sn atoms themselves which can condense on the collector optics. If Sn is used, the debris mitigation systems will need to be nearly perfect, or in-situ cleaning techniques will be needed.

This paper provides an overview of the recent EUV-related research conducted in the Plasma-Material Interaction Group at the University of Illinois at Urbana-Champaign. In the first section, candidate mirror materials will be compared under exposure to an LPP source and a DPP source. In the second section the calibrated ion energy spectra from the DPP source will be discussed. The third section describes the comparison between the exposed samples and calculations of erosion based on the measured ion flux. The fourth section explores a possible mitigation scheme for a Sn-fueled DPP, and shows the results of plasma cleaning of Sn debris.

2. LPP VS DPP EXPOSURES

Seven samples (Au, C, ML1, Mo, Pd, Ru, and Si) were exposed in the ETS LPP source at Sandia National Laboratories and have been analyzed at the University of Illinois. Samples were exposed to 500,000 shots; twenty times fewer than the initial exposures performed in the XTS DPP source at UIUC. This difference is made up for somewhat by the samples being much closer to the source in the LPP exposures (10-17 cm vs. 56 cm), and the lack of debris mitigation on the LPP source.

Analysis of the LPP-exposed samples, as well as earlier analysis of unexposed samples and a batch exposed in the DPP source, was performed at UIUC's Center for Microanalysis of Materials. Techniques performed included AFM, XRD, XRR, SEM, AES, and XPS. AFM and XRR gave the surface roughness. XRD gave information on the texture of the samples. SEM provided the best estimates of film thickness and erosion. Finally, AES and XPS measured the elemental composition of the samples vs. depth.

Six of the seven samples became rougher after exposure in the LPP source. The increase was between 1.1 and 4.5x. The metals (Au, Mo, Ru, Pd) showed the greatest increase in RMS roughness. Carbon showed a very slight increase, while the multilayer sample appeared smoother after exposure. This could occur if the ruthenium capping layer had been eroded, exposing a smooth silicon layer. There was no definite trend in roughness when comparing the LPP and DPP exposures. In some cases the LPP samples were rougher, and other samples the opposite was true.

The metallic films exhibited a fiber texture, tending to grow up from the substrate in vertical columns. The multilayer, carbon, and silicon films were harder to evaluate. The individual layers of the multilayer are extremely thin, and the silicon layers match the substrate. The silicon film is probably single crystal, like the substrate. The carbon film was either too thin to measure well or possibly amorphous. There was some decrease in average grain sizes after exposure, but for the most part XRD on the LPP-exposed samples showed little change from the unexposed or DPP-exposed samples.

In terms of erosion, the LPP samples showed less material removed than the DPP exposures. This is probably due to the shorter duration of exposure. Erosion was estimated to be between 5 nm (for ML1) and 48 nm (for Au). In comparison, the DPP erosion varied from 10 nm (for Mo) to 54 nm (for Au). Several of the samples presented problems in the cross sectional SEMs, including C, Si, and Ru. Since the erosion was not 20x less than in the DPP exposures, it can be concluded that the erosive ion flux to the samples was larger in the LPP exposures.

The LPP-exposed samples tended to be somewhat "cleaner" than the samples exposed in the DPP. In the DPP exposures, we found various elements deposited on the sample surfaces (Fe, Au, Ru, Mo) and some elements (Xe and electrode materials) deposited deep in the surfaces due to energetic impact. Future XPS depth profiling work may be able to determine more conclusively if debris ions are implanted in the LPP-exposed samples.

Complete detailed results can be found in an accompanying paper in these proceedings. An example of the data collected is shown below in tables 1 – 3.

Table 1. AFM Results for Unexposed, LPP-exposed, and DPP-exposed samples

	RMS Roughness (nm)			
Sample	Pre-Exposure	LPP-exposed	Change (exp/un-exp)	DPP-Exposed
Au	0.49	2.22	4.5	1.55
C	0.14	0.16	1.1	0.86
ML1	0.32	0.25	0.8	0.13
Mo	0.33	1.04	3.2	0.76
Pd	0.63	1.07	1.7	1.28
Ru	0.27	0.58	2.1	0.80
Si	0.09	0.16	1.8	0.26

Table 2. SEM thickness measurements for pre-exposure and LPP-exposed samples. Net erosion figures are shown for LPP and previous DPP exposures for comparison

	Thickness (nm)			
Sample	Pre-Exposure	LPP-Exposed	Erosion	DPP Erosion
Au	219	205	14	54
C	—	112	—	—
ML1	355	350	5	13
Mo	219	211	8	10
Pd	278	230	48	20
Ru	186	209	-23	-14
Si	—	—	—	—

Table 3. Grain size calculations for Au, Mo, Pd, and Ru samples

			Grain Size (nm)		
Sample	2θ (°)	h k l	Pre-exp.	LPP-exp.	DPP-exp.
Au	38.185	1 1 1	351	316	367
Mo	40.550	1 1 0	243	228	241
Pd	40.119	1 1 1	368	334	352
Ru	42.189	0 0 2	324	300	317

3. CALIBRATED ION SPECTRA FROM THE DPP SOURCE

The DPP source is an XTREME Technologies XTS 13-35 EUV source. This source flows Xenon gas into a small chamber where pre-ionization occurs initiating a 15 J discharge resulting in a z-pinch plasma column. The self-compression of this column results in heating sufficient to generate Xe^{10+} ions capable of emitting EUV light at 13.5 nm. Photons must pass through the debris mitigation region before exiting the source for collection. A commercial debris mitigation system from Xtreme Technologies GmbH is employed to modify pinch characteristics and debris output.

To measure the ion flux a Spherical Sector Energy Analyzer (ESA) is used. It is a well-characterized diagnostic capable of measuring ion energy and discriminating by charge state. These experiments use a Comstock model AC-902™ with dual microchannel plate detectors from Burle Corporation (model CP-618C™). The analyzer has line-of-sight access to the source through 2 ¾ in. CF half nipples positioned at angular intervals of 5° from 15° to 45° from the centerline of the pinch. Access at 0° is impeded by the beam stop of the debris tool. Current experiments are performed at 20° and 30° angles. Data acquisition for the ESA is triggered by the rising light signal from a photodiode. The ESA is mounted on a bellows connection to the chamber for 3 dimensional pointing control. A 1 mm orifice located proximal to the ESA limits flow to the diagnostic. Complete details of the experiment, calibration and results can be found elsewhere in these proceedings[2]. One sample result is shown below in figure 1.

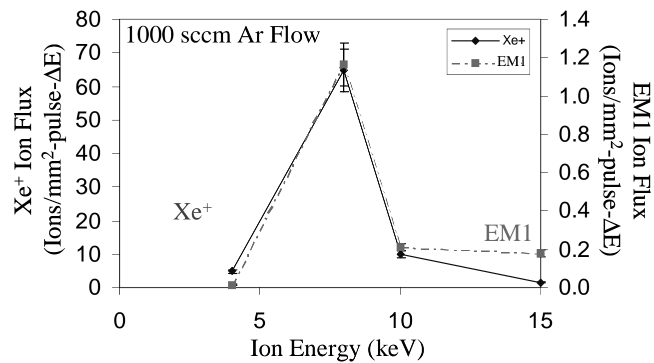

Figure1: Ion energy spectra for 1000 sccm Ar flow at 20° from centerline. The limiting orifice is 1 mm at 97 cm from the source with ΔE = 150 eV.

This figure shows the the electrode material flux is two orders of magnitude smaller than the Xe+ ions and that the mean energy is neaer 8 keV. The DPP samples were exposed to these equivalent conditions.

4. COMPARISON BETWEEN PREDICTIONS AND MEASUREMENTS OF EROSION

Knowing the ion flux allows a prediction of the sputtering that will occur on the samples. The binary collision code, SRIM was run at a energies from 1 to 15 keV and the appropriate flux in each energy range multiplied by the physical sputtering coefficient. Figure 2 shows the final result. In general, the erosion is fully consistent with physical sputtering.

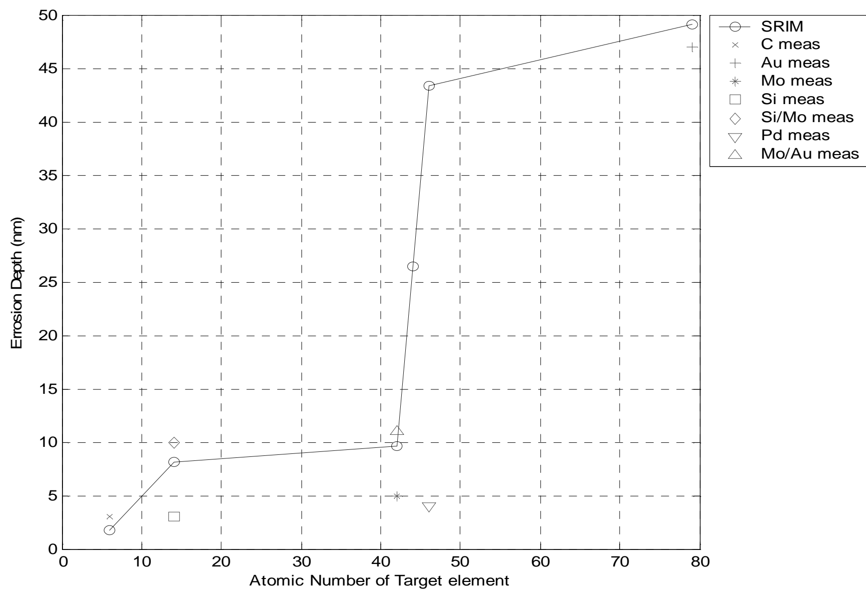

Figure 2. Predicted erosion (blue, solid line) vs measured erosion (red, disconnected)

5. MITIGATION AND CLEANING FOR SN-FUELED SOURCES

One possible method to greatly reduce the number of Sn atoms reaching the collector optics is to ionize them in a secondary plasma. Such a scheme has been put in practice in the Illinois Debris mitigation EUV Applications Laboratory (IDEAL). A high power dense rf plasma has been established in the region between the electrodes and the debris tool's foil trap. Figure 3 is a picture of the plasma obtained in this manner. Full details of the rf Sn mitigation experiment can be found elsewhere in this proceedings[3].

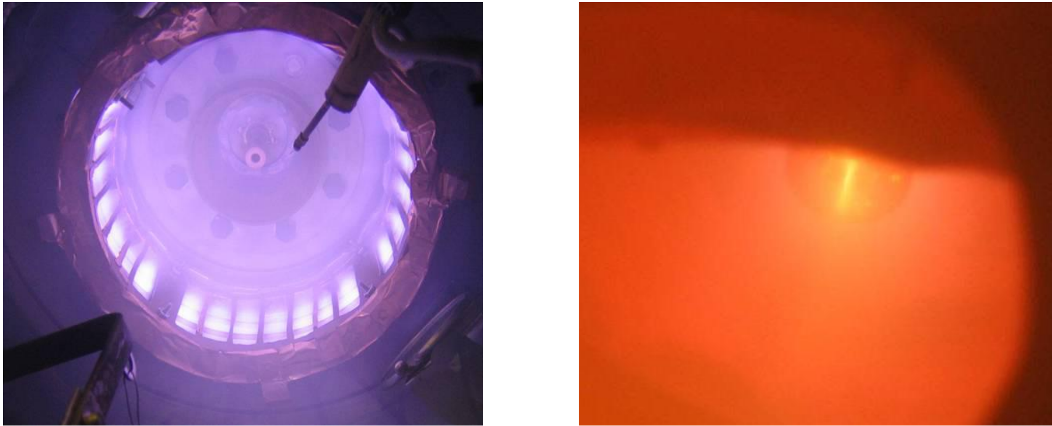

Figure 3. IDEAL secondary plasma for Sn debris mitigation and tetramethyltin DPF pinch operation.

Even with such a debris mitigation scheme, some neutral Sn atoms will diffuse to the collector optics. To rid the collector of this unwanted coating, in-situ plasma cleaning may be possible. To test such a scheme, etching experiments have been conducted to determine the selectivity of etching Sn over SiO2. SiO2 could be used as the capping layer on multi-layer mirrors.

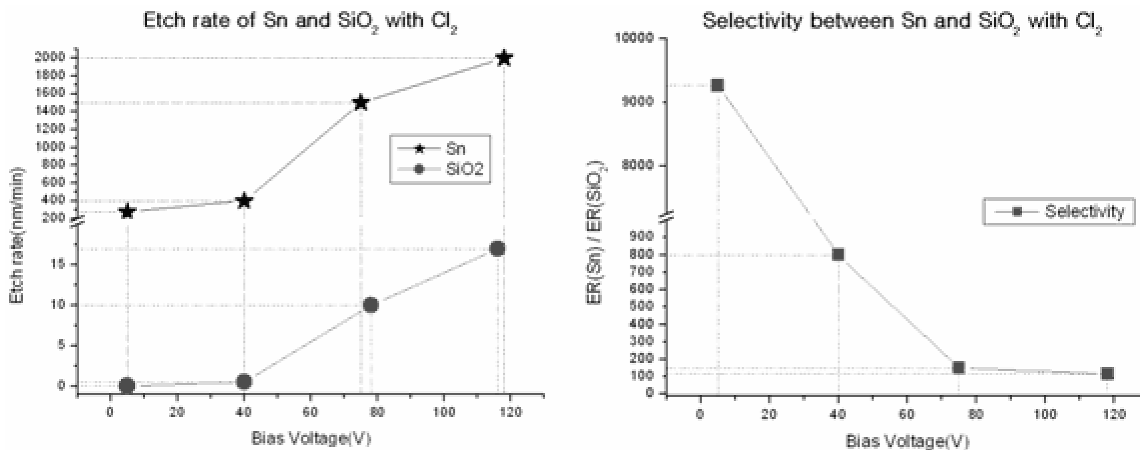

Figure 4. Etch rates of Cl_2 and HBr on Sn and SiO_2

Figure 4 shows the etch rates of Sn and SiO_2 in a Cl_2 plasma. Such an etch system may allow for periodic cleaning of the condensable Sn debris without damaging the underlying mirror surface.

6. CONCLUSIONS

Recent progress at the University of Illinois has confirmed the primary erosion mechanism for DPP Xe-fueled sources is physical sputtering. Given the similarities in the samples exposed to a Xe LPP, it is safe to say that the primary damage mechanism there is also physical sputtering. A detailed calibration of the ion flux was performed allowing absolute numbers to be determined for the first time.

In Sn work, RF mitigation has been shown to have some success and the ability to clean the mirrors by selective etching has been shown to be possible. Future work will install rf plasma mitigation on the XTS device after it is upgraded to handle Sn fuel. Etching experiments will be carried out in more realistic geometries to access the practicality of using such a technique in practice.

ACKNOWLEDGEMENTS

This work was made possible by a grant from INTEL Corporation and by SEMATECH. Valuable assistance has also been provided by Xtreme Technologies, Göttingen Germany.

REFERENCES

1. H. Qiu, D. A. Alman, K. C. Thompson, et al., "Characterization of Collector Optic Material Samples Before and After Exposure in LPP and DPP EUV Sources", SPIE Microlithography 2005, San Jose, CA, 2005.
2. E. L. Antonsen, K. C. Thompson, M. R. Hendricks, et al., "XCEED: XTREME Commercial EUV Exposure Diagnostic Experiment", SPIE Microlithography 2005, San Jose, CA, 2005.
3. M. A. Jaworski, M. J. Williams, E. L. Antonsen, et al., "Secondary RF plasma system for mitigation of EUV source debris and advanced fuels", SPIE Microlithography 2005, San Jose, CA, 2005.