Erosion and Degradation of EUV Lithography Collector Mirrors under Particle Bombardment

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ABSTRACT

In extreme ultraviolet lithography (EUVL) environments both laser produced plasma (LPP) and gas discharge produced plasma (GDPP) configurations face serious issues regarding components lifetime and performance under particle bombardment, in particular collector mirrors. For both configurations debris, fast ions, fast neutrals, and condensable EUV radiator fuels (Li, Sn) can affect collector mirrors. In addition, collector mirrors are exposed to impurities (H,C,O,N), off-band radiation (depositing heat) and highly-charged ions leading to their degradation and consequently limiting 13.5 nm light reflection intensity.

The IMPACT (Interaction of Materials with charged Particles and Components Testing) experiment at Argonne studies radiation-induced, thermodynamic and kinetic mechanisms that affect the performance of optical mirror surfaces. Results of optical component interaction with singly-charged inert gases (Xe) and alternate radiators (e.g. Sn) are presented for glancing incidence mirrors (i.e., Ru, Pd) at bombarding energies between 100-1000 eV at room temperature. Measurements conducted include: In-situ surface analysis: Auger electron spectroscopy, X-ray photoelectron spectroscopy, direct recoil spectroscopy and low-energy ion scattering spectroscopy; Ex-situ surface analysis: X-ray reflectivity, X-ray diffraction, atomic force microscopy and at-wavelength EUV reflectivity (NIST-SURF).

Keywords: sputtering, EUV reflectivity, multilayer erosion, EUV collector optics, ion scattering spectroscopy

1. INTRODUCTION

Generation of EUV light for high-resolution lithography requires the use of hot, dense plasmas. Current technology focuses mostly on either laser produced plasmas (LPP) or gas discharge produced plasmas (DPP). Both configurations require collection of EUV light with very stringent specifications. The EUV wavelength of 13.5-nm uses Xe, Sn or Li as candidate EUV radiator fuels [1]. Due to this wavelength level, reflective optics is required. For high-volume manufacturing (HVM) operation (about 100 wafers-per-hour), the collector optics must not lose more than about 10% of absolute EUV reflectivity over 10^{11} pulses or 30,000 hours. The first condenser optics is the collector and its configuration depends on the EUV source type utilized [2]. For example, the EUV light generated from LPP sources is typically collected at near-normal incidence using multi-layer mirrors. These mirrors are carefully designed to maximize reflectance in the soft X-ray region, primarily 13.5-nm. In GDPP EUV source devices, glancing incidence mirrors (GIM) are applied. These can consist of thin films of high EUV reflectivity materials (e.g. Ru, Mo, Pd, etc…). EUV light incident angles average from about 5 to 20-degrees with respect to the mirror surface.

The use of hot, dense plasmas inherently leads to generation of fast ions and neutrals at the pinch. Their energy distribution can vary depending on various factors including: EUV light generation configuration, frequency of instabilities at the pinch, optimization conditions for EUV light generation and EUV fuel types used. Some data on energy distributions from EUV light sources have been obtained for LPP configurations showing that up to several keV fast ions are possible. For the case of GDPP these measurements are less understood, however some groups are already beginning to measure such distributions. In Sn LPP systems, several hundred eV ions have been measured. In general, one can assume that the energies of fast ions and neutrals can vary from 100-1000 eV or more. The fast ion/neutral component of particle emission into the collector optics region is not the only source of debris. In addition, erosion of the electrodes leads to electrode material being ejected due to deposition of 1-2 J/cm^2 per pulse on electrode surfaces. These materials can include: copper, tungsten and molybdenum. In addition, highly-charged ions and background impurities (H, C, N, O) can be expected to interact with the collector mirror surfaces. The former, less likely so, primarily due to neutralization processes along the path from the pinch source to the mirror surface.

This paper presents results of heavy-ion bombardment on candidate collector mirror materials. Both Xe and Sn are being considered as EUV fuels. Therefore, interaction of Xe$^+$ and Sn$^+$ on Ru and Sn surfaces are presented. Ar$^+$ bombardment is also important from the perspective of its application as a buffer and or mitigation curtain gas potentially becoming an additional debris component on collector mirrors. Experiments are complemented by a newly developed code named SIBIDET that simulates the temporal and spatial depth evolution of multi-component surfaces under energetic bombardment.

2. EXPERIMENTAL SETUP

2.1 IMPACT (Interaction of Materials with charged Particles And Components Testing)

The IMPACT experiment at the Argonne National Laboratory is a versatile, multi-functional facility designed to study multi-component functional surfaces as they are modified under a variety of environments. IMPACT consists of a well-collimated ion source capable of providing an energy range between 50 and 5000 eV and fluxes of 10^{11}-10^{17} ions/cm^2/s. The sample is fixed on a rotatable manipulator, whose rotation axis lies in the plane of the sample surface. This allows for angle-of-incidence measurements of the irradiated surface 60-70 degrees with respect to normal.

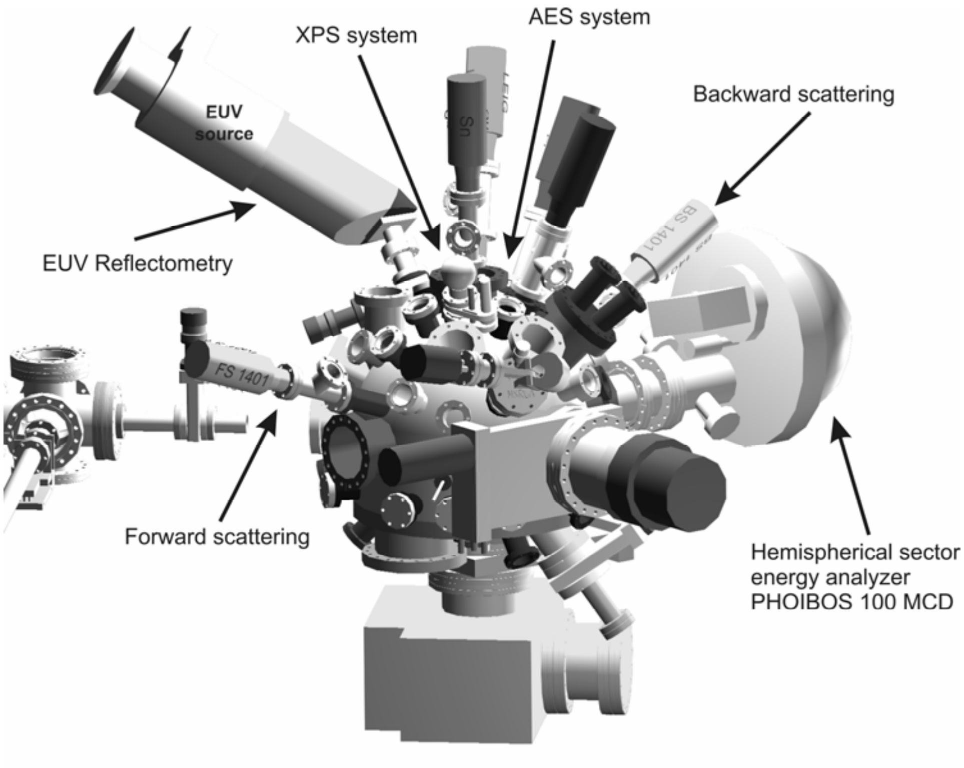

Figure 1: The new upgraded chamber of the IMPACT (Interaction of Materials with charged Particles And Components Testing) experiment at the Argonne National Laboratory. Upgrades feature additional in-situ metrology including: X-ray photoelectron spectroscopy and a EUV source for both EUV photoelectron spectroscopy (EUPS) and 13.5-nm EUV reflectometry.

Base pressures are attainable down to 10^{-9} Torr with gas inlets for controlled impurity desorption/adsorption experiments. In addition, an in-situ heating design can vary the sample temperature from ambient conditions to about

600 ºC. IMPACT has a quartz crystal microbalance – dual crystal unit (QCM-DCU) diagnostic system for in-situ real-time total erosion measurements to allow for a direct conversion from time to spatial scales during depth profiling with our in-situ surface analysis metrology. The QCM-DCU system is shown in Fig. 2 along with other IMPACT components and details of its use is described elsewhere [3]. In-situ metrology in IMPACT also include: Auger emission spectroscopy (AES) with an in-situ electron gun and low-energy ion scattering spectroscopy (LEISS). Details on IMPACT in-situ surface analysis metrology is described in the next section.

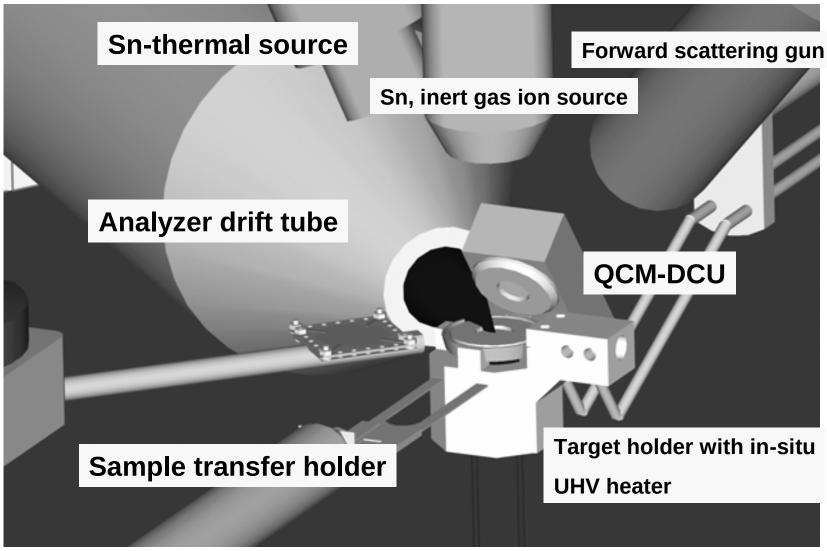

Figure 2: The quartz crystal microbalance – dual crystal unit (QCM-DCU) system in the IMPACT (Interaction of Materials with charged Particles And Components Testing) experiment at the Argonne National Laboratory.

In this paper experiments focus on the effect of heavy-ion bombardment with Ru and Sn surfaces, in particular physical sputtering. Xe^+ and Ar^+ were used at energies between 100-1000 eV at normal incidence on various samples of Ru and Sn. These experiments determined the rate of erosion of Ru SLM using the in-situ QCM-DCU system. Ru is chosen due to its high reflectivity properties for photons at 13.5-nm [4]. These studies were done at 1-keV room temperature with base pressures in the low 10^{-8} Torr. Recent measurements in EUV DPP and LPP sources show that low charge states (q = 1-2) and keV-level or below ion energies characterize the fast ion distribution near the collector optics region [5,6]. Studies at higher temperatures have been conducted as well and are presented in a different paper [7]. Surfaces are monitored using low-energy ion scattering spectroscopy as described in the next section using a hemispherical energy analyzer (PHOIBOS 100 MCD) and forward and backward scattering ion sources (1401 Nonsequitur Technologies systems).

2.2 IMPACT In-situ metrology

IMPACT uses several surface analysis techniques to monitor the mirror surface under various conditions (e.g. ion bombardment, temperature variation, gas adsorption, photon irradiation, etc…). These techniques include: low-energy ion scattering spectroscopy (LEISS), direct recoil spectroscopy (DRS), Auger electron spectroscopy (AES) and X-ray photoelectron spectroscopy (XPS). The upgraded IMPACT system will have an electron-based compact EUV light source (sem|20 by Phoenix/X-ray GmbH [8]) to conduct either 13.5-nm in-situ EUV reflectivity measurements or EUV photoelectron spectroscopy (EUPS) for top-layer surface chemical analysis complementing elemental surface analysis provided by LEISS. The combination of using electron spectroscopies (AES and XPS) and LEISS allows for various probing depths since AES and XPS gives information from 10-30 Å down to 100 Å and LEISS the top 1-2 monolayers. In LEISS an ion beam is directed at the surface, and a certain number of ions are elastically scattered at different angles. With the use of an electrostatic energy analyzer, the energy of the scattered particles can be determined, and by use of binary collision theory the mass of the atom that caused the scattering event can be determined. The resolution of this technique is based on neutralization mechanisms that result in backscattered *ions* containing information only of the topmost layer of the surface. Scattering from subsurface layers using noble gas ions for scattering is negligible due to the high neutralization probability of noble gas ions. Sample spectra for He^+ scattering at 90-degrees between the ion source and the detector is shown in Fig. 3. Note that scattering from higher masses corresponds to a higher scattered energy for the incident He ion. Also note that scattering from similar masses, for this particular scatter angle (90-degrees), is particularly difficult to resolve. In IMPACT this difficulty is addressed by providing for simultaneous forward, normal and backward scattering for various noble gas masses and energies. This is important since for backscattering angles (90-180 degrees) the mass resolution is high, yet the intensity is low; while in forward scattering mode (20-90 degrees) the mass resolution is poor while the intensity is high. In addition, at forward scattering angles, one can use direct recoils to provide information on surface impurity adsorbates. IMPACT uses an angle of 145-degrees for backscattering, 35 and 65-degrees for forward scattering, and scattering at 90 degrees. In addition, IMPACT is also equipped with a low-energy Li ion source in forward scattering geometry for alkali-ion low-energy scattering spectroscopy for surface structure measurements. Having this capability, IMPACT, can measure simultaneously variations on the surface for similar heavy masses, such as Sn on Ru using backward scattering and surface impurities (e.g. H, C, O or N) using forward scattering; all in real time during surface modification by ion irradiation, thermodynamic variations or exposure to thermal atom sources. To minimize the effect of ion spectroscopy on modification of the surface, these ion sources are optimized to give the highest possible signal for the lowest possible dose. The effect of ion scattering on possible surface damage viz ion-induced desorption is readily measured with the in-situ QCM-DCU system sensitive to sub-monolayer erosion.

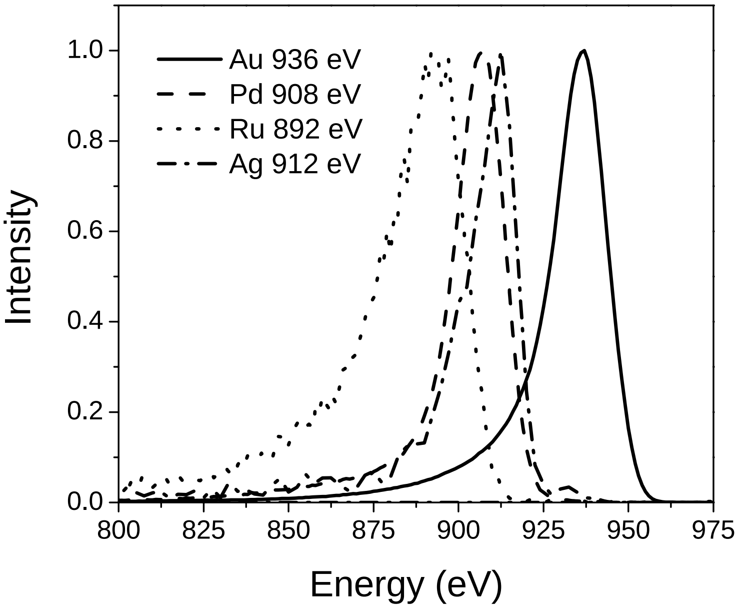

Figure 3: Ion scattering spectroscopy (ISS) scans of different elements obtained by measuring the energy of 1 keV He ions scattered at 90° with respect to the detector.

3. MODELING OF SURFACE EVOLUTION

SIBIDET (Simulation of Ion Beam Implantation in Dynamically Evolving Targets) is a BCA Monte Carlo code under development in our group to study dynamic behavior of targets during ion beam bombardment. In structure, SIBIDET is very similar to the TRIDYN code developed by J.P. Biersack, which is the dynamic version of the more popular *static* code TRIM [9]. The primary difference between static and dynamic version, is that in the former no time-dependent kinetic mechanisms can be studied. SIBIDET (Simulation of Ion Beam Implantation in Dynamical Evolving Targets) is a binary collision code that uses the Monte Carlo method to study the interaction of bombarding ions with the target atoms. It uses the “magic” scattering formula to treat collisions between atoms, and uses the scheme used in the TRIDYN code to track all the recoil atoms generated during the collisions. This enables determination of where the recoil atoms come to rest, so the target composition changes due to beam bombardment and target erosion can be tracked during the run. The target composition is updated every time a user-defined number of flights have elapsed, so the next batch of particles interacts with the "updated" target. Another number of flights interval can be specified to generate a snapshots of the target as output.

The Simulation of Ion Beam Implantation in Dynamical Evolving Targets (SIBIDET) code has been upgraded in order to incorporate the implanted species into the target. This enables one to determine the distribution of implanted particles inside the target and their effect on the target composition as it is bombarded by the ion beam. The code is able to simulate both the near-surface region and bulk regions for multi-component and multi-layer systems.

Some of the information that can be obtained with SIBIDET simulations includes:

- Interlayer mixing of components
- Preferential sputtering as a function of fluence
- Changes in surface composition with respect to bulk composition
- Erosion rate and partial sputter yields
- Quasi-equilibrium conditions for simultaneous deposition and erosion

The ability of SIBIDET to model a dynamic target allows it to address issues such as loss of reflectivity due to interlayer mixing (for normal incidence multilayered mirrors) or loss of material (for grazing incidence single layer mirrors), erosion rate (closely related to mirror lifetime), effect of implanted fuel on mirror structure and performance, etc. Other computer codes that do not modify the target composition and thickness as it is bombarded by the ions are not capable of modeling such phenomena, and they can only give accurate information during the erosion of a thick layer.

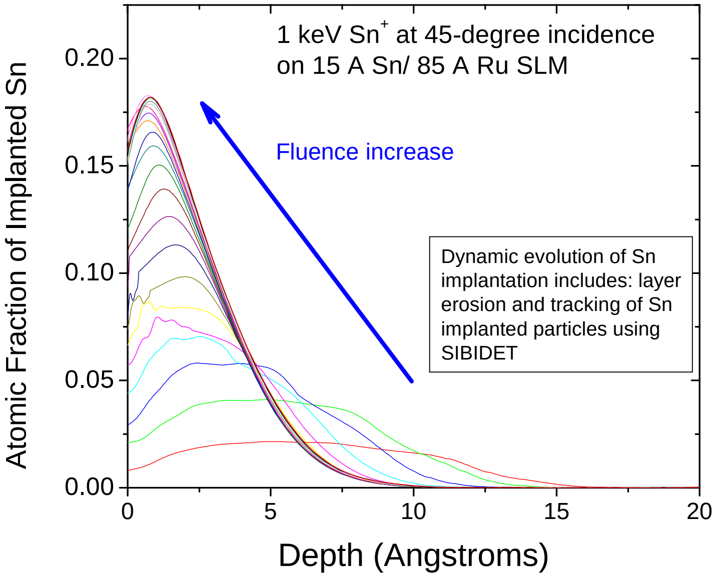

Figure 4: SIBIDET simulations of 1-keV Sn implantation profiles at 45-degree incidence with respect to Ru SLM surface normal for various fluence levels.

There are aspects of plasma-mirror interactions that can not be currently modeled with SIBIDET, which include:

- Chemical interactions between species in the mirror (such as oxidation and silicide formation)
- Thermodynamic effects (interlayer thermal diffusion, Gibbsian segregation)
- Surface roughness changes due to ion bombardment

There are long-term plans to incorporate such issues into the code in order to increase the accuracy of the model and help determine the impact of these issues in mirror performance. The code has been used to model several cases that highlight effects of ion bombardment on the EUV mirror. They can be broken down into 4 cases: (1) Light projectiles on MLM, (2) Heavy projectiles on MLM, (3) Light projectiles on SLM, and (4) Heavy projectiles on SLM. We present in this paper work for heavy projectiles (Sn) on a single-layer Ru mirror with a 15-Å Sn layer on top. Figure 4 shows an example of a 1-keV Sn^+ simulation at 45-degree incidence on a Sn-covered Ru SLM system. The figure shows snapshots for several values of fluence. The strength of SIBIDET is the ability to track the implant as a function of time. When SIBIDET is coupled to experimental data in IMPACT it makes for a powerful tool to qualify candidate materials used as SLM or MLM systems in EUVL sources.

4. RESULTS AND DISCUSSION

Heavy-ion bombardment on candidate SLM systems will lead to removal of thin-film optical surfaces and consequently degradation of EUV reflectivity in EUV sources. IMPACT results show physical sputtering yields for candidate EUV radiator fuels (Sn, Xe) on Ru and Sn surfaces. Sn surfaces are necessary to be investigated since the use of Sn as an EUV fuel could potentially lead to a thin condensable layer on the mirror surface. Fast ions and neutrals have been found to vary from a few keV down to 100's of eV. Therefore particle energies were varied from 100 eV up to a few keV. Figure 5 shows the frequency difference data for Ar on Ru at various particle energies. The data is plotted against time and regions of erosion indicated by frequency difference decrease are observed as the ion source is turned on. Background data is taken prior to each data point as indicated by the nearly flat frequency response. The data set was taken with a special low-energy 1402 ion source by Nonsequitur Technologies featuring ion beam currents up to 1-μA in a 1-mm beam spot at an energy of 100 eV. This gives enough flux for low-energy sputter data to be taken in the span of about 1000 seconds. The frequency difference data is then converted to a sputter yield after accounting for the appropriate collection geometry and sticking coefficient on the gold-covered quartz oscillator of the QCM-DCU system.

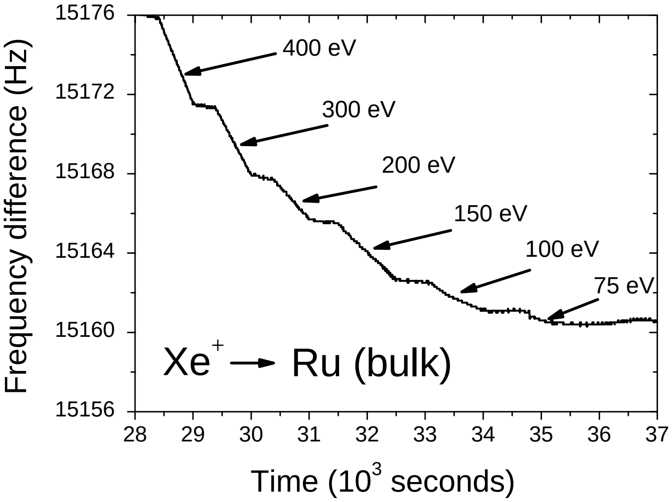

Figure 5: Frequency difference from the QCM-DCU system showing regions of sputtering by Ar^+ bombardment on Ru SLM system. This data is used to obtain sputter yield curves shown in the next section.

Figure 6 shows physical sputter data for Ar, and Xe ion bombardment on Ru surfaces (bulk and SLM). Data for Sn ions on a surface made up mostly Sn and Ru atoms is also shown for comparison. Sputter yield data from the literature is also shown for comparison. The sputter yield behavior shows some interesting trends. The magnitude of the sputter yield varies little between Ar and Xe bombardment of Ru. Similarly it is also known from experiments in IMPACT that for heavy-ion sputtering of Xe on Ru the sputter yield varies little with angle-of-incidence [3]. The data in IMPACT is comparable to data in the literature and shows that the sputter yield at 100 eV is equal to 0.1 atom/ion and up to 1.0 atom/ion for energies near 1 keV. Note the sputter yield does not yet reach a maximum at energies past 1-keV, however modeling simulations seem to suggest that the sputter yield will vary little between 1 keV and 10-keV. Therefore 1-keV bombardment for these systems is indicative of the sputtering magnitude up to 10-keV levels. The sputter yield magnitude at 100 eV is an order-of-magnitude lower than at 1-keV. This result is important since it demonstrates that if fast ions and neutrals can be slowed down even to energies to a few 100 eV, mirror erosion can potentially be reduced.

Sputtering results from a Sn surface bombarded by the same particle sources (i.e. Ar and Xe) are shown in Fig. 7. The sputter yield levels are very similar and thus one should expect that a mixture of a condensable Sn atom coverage with a Ru mirror should not vary the sputter yield behavior with energy. This is evident in the data shown on both Figs. 6 and 7. Note the data of for Sn^+ bombardment of a Sn-covered Ru mirror surface. This case is for a 1.3 keV Sn^+ source, which results in a yield comparable from sputtering from either a Ru or Sn surface. This was evident in LEISS data where the Sn atomic surface fraction reached an equilibrium on a Ru SLM system due to a balance of implantation and self-sputtering. This data also showed that Sn implantation was found in the first few monolayers, which was predicted by the SIBIDET simulations presented in the previous section.

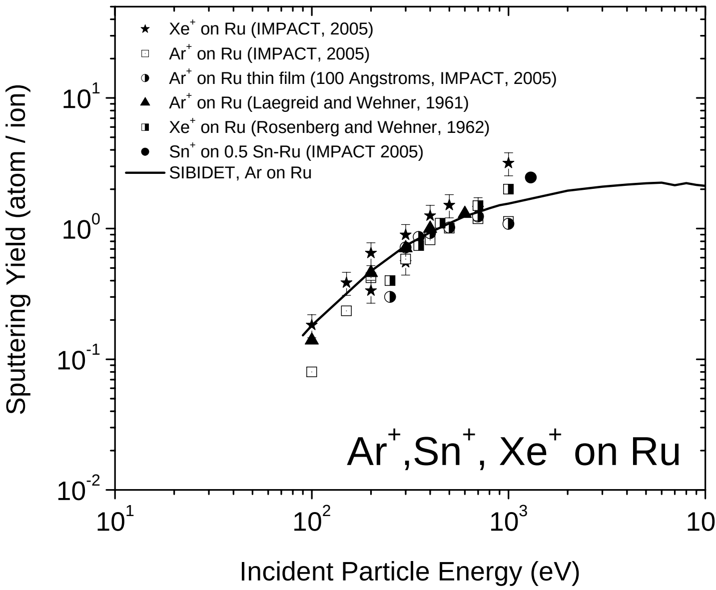

Figure 6: Sputtering yield of Ru from Ar^+, Sn^+ and Xe^+ bombardment for particle energies between 100 and up to 1.3-keV on Ru. The data was taken at normal incidence and at room temperature compared to the literature [10,11].

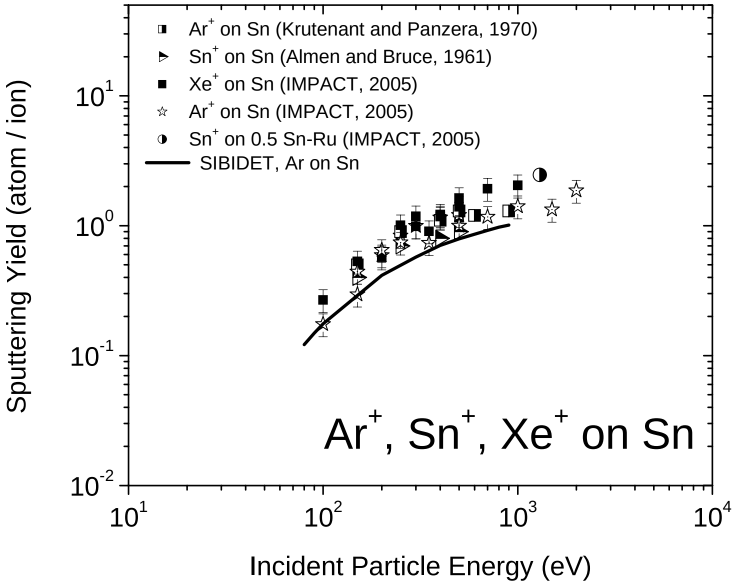

Figure 7: Sputtering yield of Ru from Ar^+, Sn^+ and Xe^+ bombardment for particle energies between 100 and up to 1.3-keV on Sn. The data was taken at normal incidence and at room temperature compared to data in the literature [12,13].

The data for Ar^+ is also relevant since Ar is the noble gas with the lowest absorption coefficient for EUV light. Therefore, Ar is typically used as a buffer gas or flowing gas curtain for slowing down of fast particles (ions and neutrals). Consequently generation of Ar ions near the collector mirror surface can lead to sputtering and according to results shown here at yields similar to Xe and Sn bombardment. Ion-induced mixing of Sn on Ru surfaces also influences the sputter yield very little since sputter yields for these systems are very close. In terms of the effect on EUV reflectivity, IMPACT results show that Sn ions are implanted on the first few monolayers and the Sn surface atom fraction reaches an equilibrium of 1:1 on Ru surfaces. EUV reflectivity is expected to change little with this level of coverage and will only decrease more than about 10% reflectivity with deposition of about a 1-nm layer.

5. CONCLUSIONS

Plasma-facing EUV source device materials will need to be carefully designed to handle the harsh environment they will be exposed to. Collector mirror optics materials have been tested in IMPACT under Ar, Sn and Xe ion bombardment. Results for particle bombardment at energies between 100 and 1000 eV show comparable sputter yield magnitudes for Ar, Sn and Xe ions on both Ru and Sn surfaces. Debris mitigation systems using Ar buffer gas, Ar flowing curtain are needed to slow particles from several keV down below 100 eV to obtain order-of-magnitude reduction in sputtering. Moreover, few sputter capping materials exist for heavy-ion sputtering at these energies including the use of tungsten or platinum. Although carbon does have substantially lower sputter yield at energies below 100 eV, their active surface with background impurities could be detrimental to EUV reflectivity performance. Current work in IMPACT on assessing the effect of fast ion irradiation under conditions found in EUV sources on in-band EUV reflectivity continue in an upgraded design exploiting in-situ metrology.

6. ACKNOWLEDGEMENTS

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