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Xe^+-irradiation effects on multilayer thin-film optical surfaces in EUV lithography

J.P. Allain [a,*], A. Hassanein [a], M.M.C. Allain [b], B.J. Heuser [b], M. Nieto [a], C. Chrobak [c], D. Rokusek [b], B. Rice [d]

[a] Argonne National Laboratory, Computational Physics and Hydrodynamics, Energy Technology Division, Building 308, 9700 South Cass Avenue, Argonne, IL, USA
[b] University of Illinois at Urbana-Champaign, Urbana, IL, USA
[c] University of Wisconsin, Madison, WI, USA
[d] Intel Corporation, Hillsboro, OR, USA

Abstract

In extreme ultraviolet lithography (EUVL) environments, transient plasma dynamics dictate conditions for particle/surface interactions. A critical challenge facing EUVL development is optical component lifetime in both gas-discharge-produced plasmas (DPP) and laser-produced plasma (LPP) devices. Optical components are exposed to impinging fast ions and neutrals, impurities (H, C, O, N) and debris, leading to component degradation and consequently limiting 13.5-nm light reflection intensity. This paper studies Xe^+ irradiation-induced mechanisms that affect the performance of EUVL multilayer collector mirror surfaces. Irradiation conditions include: incident particle energies of 1 keV and 5 keV, Xe^+ fluences ranging from about 3×10^{14}–5×10^{16} Xe^+/cm^2 and surface temperatures of 273 K and 473 K. Measurements include in situ quartz crystal microbalance for sputtering rate measurements, ion scattering spectroscopy, X-ray reflectivity and atomic force microscopy. Three distinct erosion regimes for bombardment of MLM with Xe^+ are: a low Xe^+ fluence regime below $\sim5\times10^{14}$ Xe^+/cm^2, a moderate regime at fluences between 5×10^{14} and 5×10^{16} Xe^+/cm^2 and a high fluence regime $>10^{17}$ Xe^+/cm^2.

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1. Introduction

Emerging lithography technologies include the use of extreme ultraviolet (EUV) light [1]. To generate EUV light, hot, dense plasmas are required. Two main configurations are used: laser-produced plasmas (LPPs) and gas-discharge-produced plasmas (DPPs). Both configurations also require the collection of EUV light at the first condenser optics to an intermediate focus downstream from the high-intensity plasma. Scaling to higher EUV powers hinders the application of EUV light for high-volume manufacturing lithography in the near future. Lifetime is currently defined as loss of EUV reflectivity of about 10% after operation with about 10^{11} shots.

In LPP EUVL sources, EUV light is collected at near-normal incidence with respect to the mirror surface [2] compared to DPP sources, at grazing incidence. Multilayer mirrors (MLMs) with dissimilar EUV optical constants made of Si/Mo with a period of about $\lambda/2$ are used as LPP collector optics. The conventional EUV light fuel used in both configurations is currently Xe, although Sn is also under consideration [3]. The high-intensity plasma pinch produces fast ions and neutrals that bombard nearby

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[*] Corresponding author.
E-mail address: allain@anl.gov (J.P. Allain).

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components, including the collector optics. The collector optics surface will also be exposed to off-band radiation (outside 13.5 nm) inducing heat, debris (i.e. electrode material in DPP devices), highly charged ions and background impurities (i.e. H, C, N, O). This paper studies the interaction of highly intense, fast Xe$^+$ particles on both capped and uncapped Si/Mo multilayers for LPP EUV devices.

2. Experimental setup

Interaction of materials with charged particles and components testing (IMPACT) is a new experiment in the Particle and radiation interaction with matter experiments (PRIME) facility at Argonne National Laboratory. IMPACT consists of a well-collimated ion source capable of providing ion energies between 50 and 5000 eV and fluxes of 10^{11}–10^{17} ions/cm^2/s. In this paper, Xe$^+$ energies of 1 keV and 5 keV with fluxes in the order of 10^{11}–10^{15} Xe$^+$/cm^2/s are used. The Xe$^+$ flux is measured in situ with a Faraday cup. The Xe$^+$ beam is rastered over 50–70% of the MLM sample area of 1 cm^2 at normal incidence with respect to the surface normal. Base pressures are attainable down to 10^{-9} Torr and operational pressures (with ion sources on) of 10^{-8} Torr. In addition, an in situ UHV heater holds the mirror temperature at 300 K and 473 K. IMPACT has a quartz crystal microbalance-dual crystal unit (QCM-DCU) diagnostic system used for in situ real-time total erosion rate measurements with a resolution of better than 3×10^{-3} Å/s. Low-energy ion scattering spectroscopy (LEISS) and Auger electron spectroscopy (AES) monitor the eroded surface.

Samples included two types of multilayer mirrors. One consisted of a 23 Å Ru cap layer and is denoted ML2. The other sample type consisted of a Si-terminated surface denoted ML1. Both multilayer mirrors were obtained from the LLNL group of Bajt et al. [4]. Both ML1 and ML2 had 40 bilayers with the following architecture: 45.3 Å Si/4 Å B$_4$C/23.3 Å Mo/4 Å B$_4$C. These films were grown on (100) Si substrates. Although the ruthenium caps on ML2 samples were not designed for sputtering resistance, the sputter yield from Xe$^+$ bombardment on most single-component thin-film caps (e.g. W, Mo, Re) are similar to Ru and thus these studies can elucidate on the erosion performance of these MLM systems. Table 1 lists these samples with their respective experimental conditions. Samples ML1-V and ML2-V are control samples not exposed to Xe$^+$ irradiation. Samples ML1-4 and ML2-3 were exposed to 1-keV Xe$^+$ at 298 K mirror temperature; ML1-6 and ML2-6 to low-flux 1-keV Xe$^+$ at 473 K; ML1-7 and ML2-7 to high-flux 1-keV Xe$^+$ at 473 K; and ML1-9 and ML2-4 to 5-keV Xe$^+$ at 298 K. Ex situ analysis consisted of X-ray reflectivity (XRR), and atomic force microscopy (AFM) for pre- and post-IMPACT exposure samples. XRR was performed with a Philips X'pert instrument and with a Cu Kα (8 keV) source to measure the absolute value of the first-order diffraction peak reflectivity. AFM provides a direct, real-space image of the air/film interface measuring the root-mean-squared surface roughness. AFM analysis included tapping mode with a Digital Instruments Dimension 3100 instrument and 1×1 μm scans.

3. Results and discussion

Table 1 compares the in situ erosion rate measurements taken with the QCM-DCU system in IMPACT for Xe bombardment compared to TRIM-SP simulation data. There is good agreement between simulation and experimental data. Both results show low erosion rates at low incident fluences in the order of 10^{14} Xe$^+$/cm^2, as expected. XRR results for post-exposure samples are compared with virgin samples in Table 1 and Figs. 1 and 2. A footprint correction for glancing incidence of the 8-keV photon beam resulted in an inherent uncertainty of ≈1% for our XRR measurements. The absolute reflectivity value of the first-order diffraction peak is unaffected when both ML1 and ML2 samples are exposed to 1-keV Xe$^+$ at room temperature (298 K) and low fluence. To compare, Fig. 1 shows data for sample ML3-1, which corresponds to the same bombardment conditions of sample ML1-4 except at two orders-of-magnitude higher fluence

Table 1
MLM Xe$^+$ bombardment conditions with measured first-order reflectivity, QCM erosion data and surface roughness values

Sample	Xe fluence (ions/cm^2)	Temperature (K)	Energy (keV)	R^a	σ^b (Å)	$S_{QCM}{}^c$ (Å/s)	$S_{TRIM}{}^d$ (Å/s)
ML1-V	0	294	NA	0.69	1.4	–	–
ML1-4	4.8×10^{14}	294	1	0.72	1.5	<0.001	0.002
ML1-6	5.9×10^{15}	473	1	0.55	1.5	0.065	0.024
ML1-7	5.2×10^{14}	473	1	0.57	1.2	–	–
ML1-9	3.1×10^{14}	295	5	0.54	1.3	0.002	0.001
ML2-V	0	294	NA	0.70	2.9	–	–
ML2-3	3.8×10^{14}	294	1	0.71	4.2	<0.001	0.002
ML2-6	7.2×10^{15}	473	1	0.45	1.9	0.055	0.021
ML2-7	5.1×10^{14}	473	1	0.47	3.0	0.001	<0.001
ML2-4	7.5×10^{14}	298	5	0.58	2.6	0.001	<0.001

[a] Absolute reflectivity value of first-order diffraction peak measured at $\lambda = 1.54056$ Å.
[b] RMS roughness over a 1×1 μm area measured with AFM in tapping mode.
[c] Sputter rate measured with QCM-DCU in IMPACT.
[d] Sputter rate simulated by TRIM-SP Monte Carlo code.

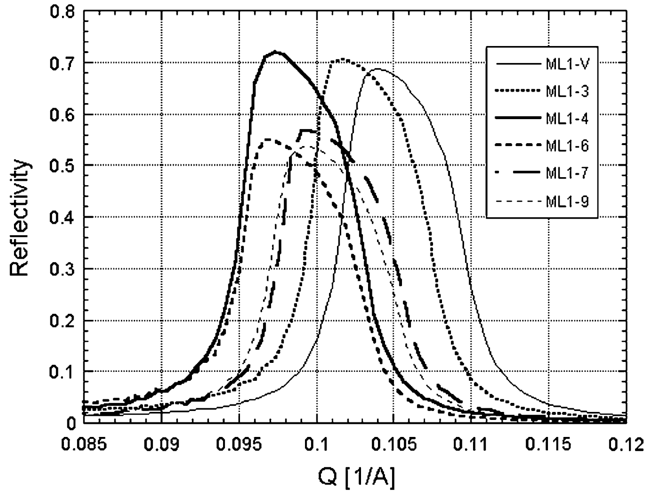

Fig. 1. Absolute reflectivity versus Q of first-order peak of ML1 samples. The wave vector transfer, Q, is defined as $Q = (4\pi/\lambda)\sin\theta$, where λ is the incident wavelength and θ is the scattering angle. Peak or maximum reflectivity values for each sample are listed in Table 1.

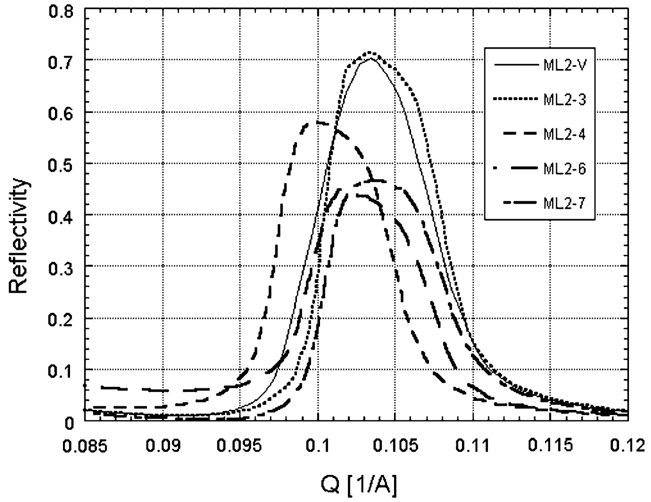

Fig. 2. Absolute reflectivity versus Q of first-order peak of ML2 samples. The wave vector transfer, Q, is defined as $Q = (4\pi/\lambda)\sin\theta$, where λ is the incident wavelength and θ is the scattering angle. Peak or maximum reflectivity values for each sample are listed in Table 1.

(4.7×10^{16} Xe$^+$/cm^2). This same sample however, eroded at a higher sputter rate averaging 0.06 Å/s. Five kiloelectron volt Xe$^+$ bombardment of MLM at room temperature (ML1-9 and ML2-4) noticeably affected reflectivity, as did 473 K 1-keV Xe$^+$ bombardment (ML1-6, ML1-7, ML2-6 and ML2-7) for both low and high fluence.

The loss of the peak reflectivity signal is due either to defects or imperfections that cause background scattering or to interfacial blurriness resulting from mixing and interdiffusion of layers in the MLM. Examination of the data in Table 1 demonstrates that the reduction of the first-order peak reflectivity is not due to increased surface roughness. Notice that all the samples with reduced first-order peak reflectivity values (ML1-6, ML1-7, ML1-9, ML2-4, ML2-6 and ML2-7) have AFM-measured surface roughness values similar to the pre-exposure values. Thus, reduced peak reflectivity does not correlate with increased *surface* roughness. The peak reflectivity reduction correlates with samples having exposures to either 5-keV Xe$^+$ or 473 K mirror surface temperature. We believe that an irradiation temperature of 473 K and high 5-keV Xe$^+$ energy induced interdiffusion of the separate Si and Mo layers, even in the presence of the B$_4$C inter-diffusion barrier. This effect is independent of the Xe fluence and degradation of the overall at-wavelength EUV reflectivity at near-normal incidence is expected. At very high fluences, $>10^{17}$ Xe$^+$/cm^2, samples showed signs of Xe bubble formation or blistering and sputter rates averaging 2.0 Å/s. Details of these results are included in a future paper.

4. Conclusions

Xe$^+$ irradiations of Ru-capped and uncapped MLM systems for various fluences, two incident Xe ion energies (1 keV and 5 keV) and two sample temperatures: 298 K and 473 K were completed. For 1-keV Xe$^+$ and 298 K, peak reflectivities remain unchanged with fluences ranging in the order of 10^{14}–10^{16} Xe$^+$/cm^2. For bombardment with 5 keV and 473 K conditions, the reflectivity response decreased, even at fluences of the order of 10^{14} Xe$^+$/cm^2. At very high fluences, $>10^{17}$ Xe$^+$/cm^2 at 1 keV and 298 K, the MLM surface showed signs of blistering. Low fluence exposures below $\sim 5 \times 10^{14}$ Xe$^+$/cm^2, had sputter rates of about 0.001 Å/s. For moderate fluence levels between 5×10^{14} and about 5×10^{16} Xe$^+$/cm^2, sputter rates average about 0.06 Å/s. And at high fluence levels $>10^{17}$ Xe$^+$/cm^2, sputter rates reach near 2.0 Å/s.

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