Laser Induced Plasma Exposure on Extreme Ultra-Violet Lithography Masks: Damage Analysis

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Abstract— Extreme Ultraviolet Lithography (EUVL) is considered as a possible next generation lithography technology for sub-22nm feature fabrication. Fabrication of zero printing defect mask blanks is one of the key challenges identified for EUVL under 16nm. One proposed cleaning mechanism is based on laser induced plasma (LIP) shock waves in which selective nanoparticle removal is possible. However, due to both shockwave thermo-mechanical loading and radiation intensity heating from the LIP core during cleaning there have been concerns over substrate damage. In current study, computational and experimental damage studies are conducted for assessing damage risk of LIP exposure to EUVL blank samples. Based on a finite element analysis, it is found that the level of radial stress on the surface of nanofilm and nanofilm layers is the critical parameter identified in both excitation mechanisms leading to mechanical material failure. Experimentally, it is determined that above a critical LIP clearance distance, no substrate damage is observed for the EUVL blank during cleaning regardless of the number of laser shots. It is concluded that pressure amplification methods and creation of residual radial tension in nanofilms could be employed to extend EUVL mask damage threshold for LIP exposure during cleaning.

Index Terms— Extreme ultra violet lithography (EUVL), laser induced plasma (LIP) cleaning, nanoparticle removal, damage thresholds, thin films.

I. INTRODUCTION

In integrated circuit fabrication, defects present on photomasks could affect image quality by creating distortions in printing of features on wafers during lithography process [1]. Ideal requirements for photomask cleaning include (i) 100% particle removal efficiency for all particles, (ii) no damage deposition to fragile structures, (iii) zero adders from cleaning process, (iv) no mask degradation and no haze and (v) no reduction in mask lifetime. EUVL (Extreme Ultraviolet Lithography), a prospective solution for fabrication of sub-22nm features, is a reflective technology as opposed to the optical masks which are transmissive, consequently it is more sensitive to mask imperfections. Fabrication of zero printing defect mask blanks as one of the major challenges in lithography of ≥ 16nm [2]. Particles and contamination are generated by usage, handling and storage of EUVL masks [3]. According to the 2010 International Technology Roadmap for Semiconductors (ITRS) update for EUVL masks, the DRAM half-pitch, specified defect sizes (\(L_d\)) and substrate defect sizes (\(L_s\)) for the year 2012 are 36nm, \(I_f = 29nm\) and \(L_s = 35nm\) respectively; while in 2019 these requirements are projected to become 16nm, \(I_f = 13nm\) and \(L_s = 24nm\), respectively [2]. Currently, manufacturable solution for removal of sub-30nm and sub-23nm defects, from EUVL substrates and blanks, respectively, are stated as not-known. LIP is a potential cleaning mechanism among several other cleaning techniques such as wet cleaning ([3], [4]) and cryogenic CO\(_2\) cleaning [5] for optical and EUVL masks. It is known that cavitation during wet cleaning (megasonic) could result in numerous surface pits on the mask blank surface after 100x cleaning at 30nm inspection [4]. Sub-30nm pits are added at a substantially higher rate than that for 50nm pits, and wet cleaning resulted in additional several small particles (~10 to 17nm). It is reported that a 10x conventional ozonated deionized water (DIO\(_3\)) cleaning process caused substantial deterioration of EUV reflectivity (~4.5%) and unacceptable critical dimension (CD) mean shift (10%) [3]. Recently, according to initial studies, cryogenic CO\(_2\) cleaning successfully demonstrated 100% damage-free and adder-free cleaning of all printable defects (both contaminants and Atomic Force Microscopy (AFM) repair debris), down to 50 nm in production environments for photomasks [5].

Smaller particles have larger adhesion force per unit particle cross-sectional area and mass compared to larger particles, thus requiring larger removal pressures, leading to significant surface damage risks. Furthermore, substrates with nanofilms often have lower damage threshold due to the substantial mismatch in the thermo-mechanical properties, weak inter-material bonding, nano-scale thickness and reduced mechanical strength compared to bulk substrates. Inherent damage mechanisms associated with contact cleaning (brush cleaning due to contact stresses [6]) and chemical cleaning technologies (cavitation with wet cleaning [7], [8]), could be problematic for cleaning of delicate structures, and dry cleaning technologies (e.g. LIP and cryogenic CO\(_2\) cleaning) are considered promising [9]-[14]. LIP damage potential on EUVL masks needs to be further investigated, as the need for damage-free cleaning technologies has been increasing.
It is known that laser ablation of nanofilms can result in material alterations such as peeling-off, mosaic patterned cracks, melting, vaporization and partial/complete removal ([15], [16]) while thermal cycling results in crack nucleation and material fatigue [17]. Cracking patterns in pre-tensioned films (surface cracks), channeling, substrate damage, spalling and debonding are observed on pre-tensioned nanofilms, while blisters, tunneling cracks, interface decohesion, tunnel cracking (or crazing) and spalling (or delamination) have been reported in pre-compressed brittle nanofilms [18].

As reported in ([9]-[14] and [19]-[24]), LIP created by focusing a high energy pulsed-laser beam to a point by dielectric breakdown of air at a clearance distance d above a substrate results in nanoparticle removal due to transient pressure loading from the generated shockwaves. Assuming no direct plasma contact with the substrate, LIP shockwaves and transient radiation heating from the plasma core are also possible sources of material alteration of the EUVL mask. In previous reports ([21], [23]), material alteration studies and computational analyses due to LIP shockwave loading and radiation heating were conducted for photomasks with 100nm chromium (Cr) films on quartz substrates. In current damage risk study, experimental and thermo-mechanical computational analyses of LIP-exposed EUVL mask blank samples with a 2.5nm ruthenium (Ru) film on 105nm thick molybdenum (Mo) and silicon (Si) multi-layer (ML) stack (i.e., 15 MLs of Mo and Si) with LTEM glass (with extremely low thermal expansion coefficient) as the substrate are reported.

II. EXPERIMENTAL SET-UP, MATERIALS AND PROCEDURE

A Q-switched 1064nm wavelength Nd:YAG pulsed-laser with a pulse energy of 370mJ, a pulse duration of 5-6ns, a repetitive rate of 10Hz, and a nominal beam diameter of 5mm was utilized for the reported LIP experiments. The EUVL mask blanks in the current study comprises of 2.5nm Ru capping layer, on 15 repeating MLs of 4nm thick Mo and 3nm thick Si creating a highly reflective surface, and utilizing a low thermal expansion material (LTEM) substrate. The Young’s modulus (E) and Poisson’s ratio (ν) for polystyrene latex (PSL) spheres used as standard particles are approximately E = 3GPa and ν = 0.33 [25]. For Ru are E=447GPa and ν = 0.3 [26], whereas the effective properties for Mo/Si MLs (assuming average properties) are approximated as E = 210GPa and ν = 0.27, respectively. The material properties for Ru and Mo/Si used in thermo-mechanical analyses are as follows: the shear moduli (G) of 171.92GPa and 88.55GPa, the mass densities (ρ) of 12300.0kg/m³ [25] and 5470.0kg/m³ [27], the heat capacities (C) of 243.0J/kg·°C [25] and 467.9J/kg·°C [28], the thermal conductivities (k) of 116.0W/m·K [25] and 3.3W/m·K [27], the coefficients of thermal expansion (CTE) (α) at 20°C of 29.0μm/m·°C [26] and 3.92μm/m·°C [25], and the longitudinal wave velocities (c₁) are calculated as 6994.4 m/s and 7385.5 m/s, and transverse wave velocities (c₂) are 3738.6 m/s and 3744.5 m/s, respectively.

The threshold (minimum) or critical clearance distance at which damage-free particle removal can be attained by LIP is needed to be determined as it is the critical process parameter for the LIP cleaning process. Previously, LIP shockwaves and the radiation intensity heating were characterized to determine whether material alterations would be initiated on EUVL masks. Utilizing transient pressure transducers, LIP shockwave pressure was acquired, shockwave temperature estimated (from gas dynamics relationships and the measured pressure levels) [21] and the radiation intensity approximated from measured radiation energy (utilizing a volume absorber type radiant power meter) ([22], [23]). A finite element (FE) analysis was conducted by using these loading conditions on thin films and obtaining the resultant stresses and surface temperature on the EUVL mask. If the surface temperature exceeds the melting temperature and/or the maximum thermally-induced stresses exceed the material yield stress, at least localized material alteration/damage could occur.

Fig. 1. Experimental set-up for LIP application on EUVL mask showing orientation of the EUV mask substrate to the LIP for particle removal or damage studies.
III. LIP Experiments for Material Alteration Analysis

In understanding the nature of LIP damage, the investigation of onset of material alterations in EUVL masks is a key due to the simultaneous presence of thermomechanical loading from shockwaves due to its thermal and pressure fields and laser radiation heating of the surface of the film/MLs.

In current study, LIP was applied at various clearance distances \(d\) and varied number of laser shots in order to (i) determine a critical clearance distance for damage-free operations regardless of the number of shots \(n\), and (ii) investigate the types and extents of material alterations/damage modes that would be observed on these delicate mask samples. The critical clearance distance \(d_c\) is defined as the safe firing clearance distance at which maximum particle removal efficiency is possible in a damage-free manner, since as the clearance distance is increased (namely, \(d > d_c\)), the force applied for particle removal reduces along with the damage potential. The experimental set-up used in the reported study and EUVL mask blank with various degrees of materials alterations are depicted in Fig.1.a. A schematic of the experimental setup is also shown in Fig.1.b. A 25 mm diameter and 100mm focal length plano-convex lens from Newport made of BK7 glass with an antireflective coating of 1064nm was utilized to converge the laser beam to create the plasma at the focal point at a specific clearance distance above the EUV mask substrate. The EUV mask substrate is moved to different impact locations directly under the focal point of the laser beam, i.e., the location of the laser induced plasma, at varied clearance distances and number of laser pulse shots.

In current study, the types and extents of material alteration possible on this class of nanofilms due to LIP thermomechanical loading were investigated by testing at 12 different clearance distances (from \(d = 1.25\) to 3.75 mm), and a varied number of laser shots (from \(n=1\) to 625). The number of laser shots at the different clearance distances tested were as follows: \(n=1\) at \(d=1.25\)mm, 3 at 1.5mm, 10 at 1.75mm, 25 at 2mm, 75 at 2.5mm, 300 at 2.75mm, 625 at 3mm, 1 at 3.25mm, 5 at 3.5mm, 20 at 3.55mm, 200 at 3.6mm and 200 at 3.75mm. It is observed that the number of laser shots could also be an important process parameter, because even if the clearance distance is increased slightly (reduced damage potential), on increasing the laser shots, more cumulative damage can be inflicted. This effect is clearly visible in Fig. 2, on comparing the optical microscope images of damage induced at a clearance distance of \(d=2\)mm and \(n=25\) laser shots (at location 4), with that at clearance distance of 2.5mm and 75 laser shots (location 5), showing that the latter case induced visibly more damage. As seen in Fig. 2, no cumulative material alteration/damage was observed for LIP exposure at a clearance distance of \(d = 3.6\)mm for \(n=200\) laser shots. Some material alterations were however observed at \(d = 3.55\)mm for \(n=20\). Thus, clearance distance of \(d_c = 3.6\)mm is inferred as the critical clearance distance or experimental damage threshold for LIP application on the EUVL mask. Material alterations, such as surface cracks, peeling, film stripping, melting and discolorations, were observed from optical microscope (Fig. 2) and scanning electron microscope (SEM) (Fig. 3) inspections of these samples.

The compositions of Mo, Si and O in an area where material alterations were intentionally inflicted on the EUVL mask due to LIP exposure is apparent in Fig. 4. Mo film layer is observed to be stripped off in the darker areas of the actual image shown in Fig. 4.d., indicating Ru film also stripped off. Correlating the material alteration to the clearance distances, the damage modes of discoloration, peeling, cracks, film/MLs stripped off, and melting are the predicted order of material alterations on decreasing \(d\) below the critical clearance distance \(d_c\) (or increasing the excitation). Discoloration is the least damaging of the material alteration.
modes observed. LIP exposure on these EUVL mask blank samples when compared to that on photomask blank samples [23], indicate more severe cracking on photomasks. In the experiments reported in current study, no material alteration/damage was observed for LIP application at a clearance distance of \(d = 3.6\text{mm}\) for \(n=200\) shots on the EUVL mask blank sample consisting of a 2.5nm Ru on 105 nm of Mo/Si MLs on a quartz substrate.

IV. PSL NANOPARTICLE REMOVAL THRESHOLD FOR EUVL MASKS

The nanoparticle removal threshold obtainable from the LIP exposure in air needs to be determined for a given particle-substrate materials pair. For these calculations, it is assumed that PSL particles are being removed from the flat Ru film (EUVL mask surface). PSL nanoparticles are often used in adhesion experiments as standards, as their physical and geometric properties are well characterized. The Hamaker's constant \((A)\) for PSL on Ru, is often given as \(2.07\times10^{-19}\text{ J}\) [26]. The material properties for PSL and Ru have been determined using the equations from the literature (e.g. [9], [14]) for calculating various relevant parameters. The angle of approach \((\theta)\) of the shock wavefront to the particle sitting on the film/substrate, i.e., the force direction at the particle, is taken to be 0 or \(\pi\). This approximation is sensible since the spherically expanding shockwave front with few millimeter radius of curvature appears as planar wavefront to the sub-100nm sized particles adhered on the substrate. For a PSL particle with the diameter of \(D=60\text{nm}\), the contact radius \(a\) is estimated as \(3.19\text{nm}\) on a Ru film/substrate, the work of adhesion \(W\) is approximated as \(34.3\text{mJ/m}^2\), the corresponding pull-off force \((F_p)\) is calculated as \(F_p = 4.85\text{nN}\) and the required pressure for removal \((P_r)\) is approximately determined as \(P_r=91.4\text{kPa}\) based on the equations reported in [14] (compared to 96.3 kPa for removal from Cr film for the photomask). The maximum available shockwave pressure \((P)\) generated by LIP in air at the various clearance distances \((d)\) is experimentally determined using a pressure transducer. This estimated pressure level is assumed to be exerted on the Ru film surface for detachment of the PSL particle. Based on [14], the maximum available LIP shockwave pressure \((P)\) at the various clearance distances \((d)\) is known, and the corresponding spherical PSL particle diameter \((D)\) that can be removed can be estimated and represented as reported in [14].

Since experimentally it is determined that \(d_r = 3.6\text{mm}\) for the substrate used here, \(d < 3.6\text{mm}\) defines the 'experimental damage zone'. Based on [14], a minimum diameter of \(D_{mm} = 59\text{nm}\) PSL is calculated as the smallest particle that can be removed from Ru film (compared to 46 nm for Cr film at \(d_r = 2.5\text{mm}\)) utilizing the LIP shockwave pressure of 93.5kPa in air for a single laser shot without any material alterations of EUVL mask blank at critical clearance distance \(d_r = 3.6\text{mm}\). So it is concluded that, in order to achieve the particle removal requirement according to the ITRS 2010 update [2], pressure amplification techniques utilizing LIP such as shock tubes [29], wet-LIP [30], and submerged shock-tubes [31] or film design approaches creating stressed-films are required.

V. THERMO-MECHANICAL ANALYSIS OF TRANSIENT LIP SHOCKWAVE LOADING

Risk of material alterations at clearance distance of \(d = 2\text{mm}\), at which experimental damage is observed due to LIP shockwave loading on a photomask sample, is evaluated and compared to response obtained for the same conditions on an EUVL mask blank sample used in current experiments [21]. The FE model for the EUVL mask is a 2.5nm Ru film on a 105nm Mo/Si substrate. MLs were modeled as a substrate with average material properties of Mo and Si (to relate to the MLs) for simplicity. A small-size FE model area with a radius of \(1\mu\text{m}\) of the EUVL mask prototype was meshed and analyzed to investigate the effect of the LIP shockwave loading on the thin Ru film.

Based on the speed of the transverse elastic wave \(c_f =3,738.7\text{m/s}\) in Ru and Mo/Si (\(c_f =3,744.5\text{m/s}\)) the maximum element size \(l_{max}\) for the FE analysis was approximated for both materials as \(3.12\mu\text{m}\), utilizing the laser pulse duration of \(\Delta t = 5\text{ns}\). For the Mo/Si MLs, the element size was chosen as 5nm. In the case of the Ru film, since the film thickness is only \(2.5\text{nm}\), \(1.25\text{nm}\) is the element width (for at least 2 elements along thickness - \(z\) direction) and \(2.5\text{nm}\) is the element length (\(r\) direction) chosen to have sufficient number of elements. The FE mesh for the 2.5nm Ru film in the finite and infinite parts has the dimensions of \(1000\text{nm} \times 2.5\text{nm}\) and \(5\text{nm} \times 2.5\text{nm}\), the element sizes of \(2.5\text{nm} \times 1.25\text{nm}\) and \(5\text{nm} \times 1.25\text{nm}\), the number of elements are 800 and 2, and the number of nodes are 1203 and 3, respectively. Similarly the FE mesh for the 105nm-thick Mo/Si layer in the finite, infinite parts on the right (along \(r\)), and below (along \(z\)) had the dimensions of \(1000\text{nm} \times 105\text{nm}\), \(5\text{nm} \times 105\text{nm}\) and \(1000\text{nm} \times 5\text{nm}\); the element sizes of \(5\text{nm} \times 5\text{nm}\), \(5\text{nm} \times 5\text{nm}\) and \(5\text{nm} \times 5\text{nm}\); the number of elements are 4200, 21 and 200; and the number of nodes are 4422, 21 and 201, respectively. This axisymmetric FE mesh consists of 5,223 elements, 5,850 nodes with 17,325 degrees of freedom. The temporal step size for the simulation is 5ps, and the total simulation time period is 5.592\(\mu\text{s}\). The fully-coupled linear thermal-mechanical transient analysis was conducted in the commercial finite element analysis package ABAQUS™. Axi-symmetric four-
ΔT - res in the range of ~425K, this may not be ss
σ 21 q. 1 α - is MPa) reported in σ σ σ oupled temperature 
σ τ . the thermal (radial) stress (τ), the thermal (radial) stress
Δr free) =

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node solid element (coupled temperature-displacement), CAX4RT, was used for the Ru film and the Mo/Si MLs, while at the free boundary of the model an infinite (reflection-free) element type, CINAX4, was employed similar to [21]. 

LIP shockwave pressure (mechanical loading) and thermal (thermal loading) waveforms obtained from the thermo-mechanical analysis on the photomask prototype were similarly applied on the EUVL mask prototype. The transient temperature rise on the top surface of the Ru film is depicted in Fig. 5.a. for consecutive segments with the width of Δr = 87.5μm (for ten segments from r = 0.0mm to 0.875mm). The transient response waveforms are the same as the time profile of the applied temperature excitation since this load is the boundary condition prescribed on the top surface of the film, and no heat loss was considered due to the short (microseconds) time-scale of the problem, which is too fast for substantial convection and conduction to take place at this length-scale.

The maximum temperature rise on the Ru film surface of ΔT = 152K (Fig. 5.a.) implies temperature of 450K which is 5.74x lower than the Ru melting point of 2,583K [25], and though this is not of thermal damage concern to Ru film itself, this does not apply that the Mo/Si layers or the interface of Ru and the underlying Mo/Si layers would not be damaged. In the results presented, reflectivity loss of the EUV mask has been ignored. It is to be noted that though EUV reflectivity loss and silicide formation in the metal/silicon interface are possible, with temperatures in the range of ~425K, this may not be reached with the shockwave loading as 450K was attained at clearance distance of d=2mm, and the safe clearance distance of d=3.6mm would result in a lesser surface temperature rise. The three components of the stress tensor on Ru film surface are radial stress (σrr), axial stress (σzz) and shear stress (τrz) induced by the LIP shockwave. The radial stress σrr is the same as the circumferential stress σθθ due to the symmetry of the model. The radial stress σrr near the film surface (Figure 5.b.) reaches a maximum of 2.25GPa around the impact point O, and then decreasing with a smooth profile similar to the shockwave propagation pressure loading curve. The ultimate tensile strength of hot rolled Ru is reported as 540MPa [25]. The shear stress τrz increases from zero around the impact point O, reaching a maximum of nearly 20MPa. The maximum τrz at different points along the film surface represents the shear stress profile when the shock wavefront passes each FE integration point. The axial stress σzz reaches a peak of 305kPa. The resultant radial stress (σrr) of 2.25GPa obtained for LIP shockwave thermo-mechanical loading on the EUVL mask prototype is ~3.5x of the resultant radial stress on the photomask prototype (649.1MPa) reported in [21]. This result was expected because of the 2.5nm thin Ru film on EUVL mask compared to the 100nm (~2 orders of magnitude thicker) Cr film on photomask.

The radial stress σrr (and circumferential stress σθθ) on the EUVL mask prototype are computed to be remarkably larger, four orders of magnitude than the axial stress σzz and two orders of magnitude larger than the shear stress τrz respectively. For an isotropic and linearly elastic case, based on coefficient of thermal expansion (CTE) mismatch between Ru (film) and Mo/Si (MLs), the thermal (radial) stress (σrr) generated due to a temperature elevation ΔT of 152K can be estimated for thin films (thus with very low inertia) by [18]

\[
\sigma = \frac{E_f (\alpha_s - \alpha_f) \Delta T}{1 - v_f}
\]

where (αs - αf) is the CTE mismatch between the Mo/Si substrate (s) and Ru film (f), v_f the Poisson’s ratio of Ru, E_f the Young’s modulus of Ru film and ΔT the resultant temperature elevation taken to be 152K from the FE analysis of the thermo-mechanical shockwave loading (from Fig. 5.a.). The obtained stress (σ) is compressive if αs < αf , as in the present case as CTE of Mo/Si is lower than that of Ru. From the FE analysis, LIP shockwave loading resulted in a temperature elevation of 152K and radial stress of 2.25GPa on the Ru film, this temperature rise when utilized in Eq. 1 gives an estimated radial stress of 2.33GPa, indicating good agreement with the FE results.

It is noteworthy that LIP shockwave loading at a clearance distance of d = 2mm, generated utilizing the 370 mJ pulsed laser, on a photomask and EUVL mask, resulted in film surface radial stress σrr of 649MPa and 2.25GPa, respectively. Radiation thermal loading rather than shockwave loading is the main damage concern for photomasks [21]. Ru film surface temperature rise and stress components obtained for the EUVL mask prototype are an approximation of the dynamic transient response to LIP shockwave loading, since
the Mo/Si MLs was modeled as an effective medium with average material properties of Mo and Si, and further the quartz substrate beneath the ML’s was not modeled. This was due to the difficulty to run a very fine mesh as the film is so thin (2.5 nm Ru), and high aspect ratio elements cause accuracy problems in FE analysis. The element size chosen for the Ru film was 1.25 nm x 2.5 nm. The objective here was to obtain an approximate rule for the critical Ru film radial stress component due to LIP shockwave loading, as the temperature rise and other stress components are not expected to be the critical damage concern.

VI. ANALYSIS OF TRANSIENT LIP RADIATION HEATING

Thermo-mechanical analysis was conducted for LIP radiation intensity heating on an EUVL mask prototype to obtain sustainable film surface temperature and induced stresses as was done for the case of the photomask ([21], [23]). A thermo-mechanical investigation of a Ru film on Mo/Si substrate (average properties of Mo and Si taken for a single layer instead of several MLs) is explored by a dynamic and fully-coupled linear thermal-stress analysis (using explicit integration scheme) conducted using ABAQUS™. The thermal skin thickness of Ru is approximated as

\[ \delta = 4 \sqrt{\frac{\Delta T}{k/2\pi}} = 703\text{nm} \]

since the Ru film thickness is much lower (2.5 nm), the Mo/Si with \( \delta = 761\text{nm} \) would have a significant effect on the Ru film. In the above formula, the laser pulse width \( \Delta t = 5\text{ns} \), and thermal diffusivity of \( k = 38.8 \times 10^{-6}\text{m}^2/\text{s} \) and \( 45.48 \times 10^{-6}\text{m}^2/\text{s} \) for Ru and Mo/Si are used, respectively. The film surface temperature (\( T \)) and the radial (\( \sigma_r \)), axial (\( \sigma_z \)) and shear (\( \tau_{rz} \)) stress components are linearly proportional to the laser intensity (\( I_o \)), as the FE material model adopted is linear. An axi-symmetric FE mesh for a 2.5nm Ru film with the element size of 1.25nm x 7nm on 105nm Mo/Si with the element size of 35nm x 35nm with a radius of \( R = 210\mu m \) with infinite elements at the ends (right side along \( r \) and below along \( z \)) is utilized for the simulation of the radiation intensity heating (\( I_o = 1\text{GW/m}^2 \)) of the Ru film due to LIP exposure.

An indirect and non-contact technique has been utilized to approximate surface temperature rise due to a nanosecond LIP radiation exposure. LIP radiation energy per pulse is measured using a radiation power meter, and the measured energy is superimposed over the known LIP irradiation profile, and this re-normalized intensity is applied as input for the fully coupled FE analysis. The transient thermo-mechanical response of the Cr film on photomask due to LIP radiation intensity loading was obtained and reported in [22], and similarly the Ru film response for a EUVL mask was obtained in the current study. The normalized radiation intensity amplitude of \( I_o = 1\text{GW/m}^2 \) and normalized radiation intensity profile \( A(t) \) was uniformly prescribed as distributed surface heat flux on the entire Ru film surface. Note that in these approximations, the laser radiation intensity profile \( A(t) \) is assumed not to change with the clearance distance (\( d \)), only the amplitude varies since the LIP core diameter is large compared to \( d \) and the damage zone size. In the FE analysis, for both Ru and Mo/Si, axi-symmetric coupled temperature-displacement solid elements were utilized, while the free boundary was modeled with infinite (reflection-free) elements. The resultant Ru film surface temperature rise (\( \Delta T \)) of 159K (Fig. 5.c), radial stress (\( \sigma_r \)) of 2.94GPa (Fig. 5.d.), axial stress (\( \sigma_z \)) of 1.43MPa and shear stress of (\( \tau_{rz} \)) of 2.3MPa were obtained. The radial stress component (Fig. 5.d.) dominates the shear and axial stress components. In forming a damage threshold criterion, it is to be determined whether the radial stress (\( \sigma_r \)) which is the most critical stress component for damage, exceeds the dynamic yield strength of the Ru film and/or the surface temperature (\( T \)) reaches the melting point, to predict whether Ru film damage/material alteration would occur due to LIP radiation intensity heating. Utilizing \( \Delta T = 159\text{K} \) (from the obtained FE results for radiation intensity heating Fig. 5.c.) in Eq. 1, the magnitude of the thermal (radial) stress (\( \sigma_r \)) that is generated due to this temperature elevation (\( \Delta T \)) estimated to be 2.89GPa, which is close to the value of 2.94GPa that was obtained from the FE simulations. This observation indicates that the results of the FE simulations for radiation intensity heating are in good agreement with the isotropic linear elastic case approximation utilizing Eq. 1, for the Ru film. Both irradiative transient heat and the transient heat from the transient hot gas exposure (shockwave front) results in compressive stresses on the film (initial compression of the film in the axial direction and follow-on expansion in the radial direction). The thermo-mechanical expansion of the thin film is predominantly responsible for the compressive (in the radial direction) induced stress field (\( \alpha_s < \alpha_o \) for Mo/Si compared to Ru).

At the experimental damage threshold, the safe/critical clearance distance of \( d = 3.6\text{mm} \), the radiation intensity calculated is \( I_o = 7.14\text{GW/m}^2 \). Since the FE model is linear, and the applied radiation intensity was \( I_o = 1\text{GW/m}^2 \), the temperature rise and stresses obtained need to be multiplied by \( I_o / I_o = 7.14 \) to obtain the actual values. The Ru film damage limits for maximum radial stress \( \sigma_r \) and surface temperature \( T \) are therefore estimated as 21GPa (= 2.94GPa x 7.14) and 1433K (= 159K + 298K) for the LIP radiation intensity loading at critical clearance distance \( d = 3.6\text{mm} \). The computational results for the peak amplitudes of the Ru film surface temperature rise (\( \Delta T \)), radial (\( \sigma_r \)), axial (\( \sigma_z \)) and shear (\( \tau_{rz} \)) stresses, for the two cases of (i) LIP shockwave thermo-mechanical load (shockwave temperature and pressure) at \( d = 2\text{mm} \) are 152K, 2.25GPa, 0.305MPa, and 20MPa; and (ii) laser radiation intensity heating at \( d = 3.6\text{ mm} \) are 1135K, 21GPa, 10.2MPa and 16.4MPa, respectively. No reflectivity was assumed in the current study, and reflectivity reduces the film surface responses obtained for the photomask case, and any reflectivity loss of the EUV mask substrate was ignored. It is to be noted that in order to get a more accurate estimate of the surface temperature limit for the EUV mask damage,
optical reflectivity (wavelengths 190 to 1000nm) and EUV reflectivity (13.5nm wavelength), measurements need to be taken after processing with the laser induced plasma at different heights to find the critical height below which reflectivity changes are seen on the EUV blank mask. This can then be utilized as the new safe clearance distance to be used for the particle removal, which could probably be greater than the currently determined 3.6mm. New thermal and pressure waveforms can be obtained and set as input condition for the computational simulations to calculate new damage threshold estimate for the Ru film surface temperature.

The radial stress component \( (\sigma_r) \) of the film is determined as most critical for damage concern in LIP shockwave loading as well as laser radiation intensity heating. It is observed based on the FE analyses, that the thermo-mechanical responses of the Ru film surface (radial, axial stress and temperature rise) due to laser radiation intensity level \( (I_r) \) heating at \( d = 3.6 \) mm is almost an order of magnitude higher \((-9.33 \times \sigma_r, \text{ and } -7.5 \times \Delta T)\) compared to those due to the LIP shockwave thermo-mechanical load at \( d = 2 \) mm. Since, the responses of LIP shockwave at safe clearance distance \( d = 3.6 \) mm, will be lesser in magnitude than the damage prone clearance distance of \( d = 2 \) mm, it is clearly concluded that LIP radiation intensity loading is of damage concern rather than LIP shockwave for the Ru film on EUVL mask blanks (same conclusion reported for photomasks [23]). No melting is expected for the Ru film surface temperature of 1433 K (temperature rise of 1135 K) as the melting point is 2583 K [25] due to LIP radiation heating. This does not imply that there would be no damage of the underlying Mo/Si layers or the interface of the Mo/Si and the Ru film. EUV reflectivity change and possible silicide formation in the metal/silicon interface, possible at high temperatures in the range of \(-425\)K, are ignored. Visual damage of the Ru film is considered as the damage criteria in the current damage study. Thus, no material alterations/damage is expected if the nanofilms on the EUVL masks are able to withstand the radial stress due to combination of LIP radiation heating and shockwave loading. It is to be noted that in the current experiments the pulse energy was 370mJ for the laser that was utilized. This was the laser that the authors conducted particle removal experiments previously on silicon wafers and then utilized for the determining damage on photomasks and EUV masks. The safe clearance distance determined here is specifically for this laser, so if a lower power laser was utilized, then it would have a larger safe clearance distance, and consequently a different associated cleaning efficiency.

VII. CONCLUSIONS AND REMARKS

Laser induced plasma generated shockwaves is a possible cleaning mechanism to satisfy the critical need for selective damage-free cleaning of nanoparticles from EUVL masks, required for sub-50nm lithography. The objectives of current investigation include (i) experimentally obtaining safe clearance distances for damage-free selective nanoparticle removal and (ii) understanding the thermo-mechanical effects and onset of material alterations due to the LIP shockwave and radiation heating from the plasma core. With a 370mJ, 5-6ns pulsed Nd:YAG laser at a wavelength of 1064nm, it is determined that the critical clearance distance of \( d_r = 3.6 \) mm below which material alteration/damage would occur was experimentally obtained. With increasing \( d \) or decreasing level of excitation, the observed order of material alteration modes in EUVL masks due to LIP exposure is as follows: melting, stripping off of film/MLs, cracks, peeling and discoloration (the most minor material alteration). EUVL masks are determined to be substantially weaker (larger \( d_r = 3.6 \) mm) compared to the photomasks \( (d_r = 2.5 \) mm) for onset of material alterations due to LIP exposure with the same pulsed-laser. It is predicted that damage-free cleaning of 59 nm and 46nm standard PSL particles are possible utilizing LIP shockwaves from Ru and Cr films, respectively. Removal of sub-50 nm particles from EUVL masks require utilization of LIP pressure amplification techniques [29]-[31]. It has been reported that pressure amplitude can be increased from the same LIP source by using various types of shocktubes [29]. It is determined that, if/when dynamic yield stress is exceeded, the Ru film surface radial stress component \( \sigma_r \) is the critical damage concern for the thermo-mechanical LIP radiation heating \((-9.33 \times \sigma_r, \text{ of LIP shockwave loading})\). Ru film surface temperature rise is not expected to be the critical damage concern for EUV masks. Reflectivity change of the EUV mask was ignored in these experiments, therefore to get a more realistic estimate of the Ru film surface temperature threshold, optical and EUV reflectivity measurements at different heights of LIP exposure are suggested. The damage limit for Ru film surface radial stress \( (\sigma_r) \) is determined at the critical clearance distance \( (d_r = 3.6 \) mm) for its thermo-mechanical response. It is noteworthy that neither optical reflectivity nor penetration was taken into consideration in these calculations, incorporating the reflectivity would lower the film surface thermo-mechanical responses, enabling removal of smaller particles than included above. Thermal loading leading to mechanical material failure is determined to be of the key damage mechanism for nanofilms under LIP. It is concluded that residual radial tension induced during deposition in the Ru film could also increase the EUVL damage threshold due to LIP radiation exposure (compressive stresses) by lowering the resultant stresses in the films.

REFERENCES

Defectivity and Lifetime”, International Symposium on EUV Lithography, Kobe, Japan, October 18, 2010.
[26] Private communications, INTEL Corp.