Plasma-Assisted Electrostatic Cleaning of EUV Masks

W. Lytle, H. Shin, D. Ruzic

Department of Nuclear, Plasma, and Radiological Engineering

University of Illinois at Urbana-Champaign. Correspondence to druzic@uiuc.edu

http://starfire.ne.uiuc.edu

Abstract

Plasma-Assisted Cleaning by Electrostatics is a dry-cleaning process that uses substrate-particle charge imbalance as well as trapped surface charge to propel contamination off the surface. Through using an electron gun and a weak local plasma to charge the particles, satisfactory charge imbalance can be accumulated for removal. Charging the particles produces an image charge on conducting substrates, however utilizing a high flux density of electrons, the image charge is partially screened allowing for the electrostatic repulsion necessary to remove contaminants. This electrostatic repulsion can be further increased by pulsing the plasma. When the plasma is turned off, electrons quickly exit the plasma leaving the heavier ions behind and momentarily increases the contamination's charge in the presence of an electric field. The benefit of PACE is the quickness in which a surface may be processed since the entire surface can be cleaned at once. Results of cleaning 30nm polystyrene latex (PSL) spheres from Si wafers showed nearly complete removal. Recent tests on chrome on quartz patterned masks has shown no pattern damage. Cleaning of silicon, quartz, and ruthenium coated quartz substrates and damage assessment of features is in progress for the removal of Si_3N_4, Al_2O_3, PSL's, and Au nanoparticles

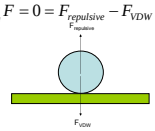
Motivation

In Optical Lithography, a pellicle is used to protect the reticle from becoming contaminated. In EUV lithography, no material is transparent to 13.5 nm light. The lack of a pellicle in this case allows the reticle to become "dirty" and the necessity to be cleaned in order to maintain processing throughput.

Particle Adhesion Theory

Force balance on the particle

$$\sum F = 0 = F_{repulsive} - F_{VDW}$$



F_{vdw} is in the range of 10^{-12} to 10^{-9} Newtons

In order to remove particles, we need to provide enough electrostatic force in order to overcome F_{VDW}.

Particle Removal Theory

Need to satisfy $F_{repulsive} > F_{VDW}$

$$\vec{F}_{repulsive} = q_p \vec{E}_{sheath}$$

where q_p= the total excess charge on the particle and E_{sheath} is the electric field in the plasma sheath region

Two parts of the equation to analyze

(1) How to determine the value for q_p

(2) How to determine the value for E_{sheath}

How Does PACE Remove Particles

- Apply a pulsed DC bias to the sample
- Use a plasma to charge the particle up more negative (positive sample bias)
- Modify the plasma sheath potential to create a larger electric field (negative sample bias)
- Particles are removed by $F=q_pE_{sheath}$

How to Determine q_p: Max Charge on the Particle (1)

Do an energy balance of the system:

$$E = \frac{(q_e)\cdot q_p}{4\pi\varepsilon_0 r_p} + |(q_e)\cdot \Delta V|$$

E = the energy of the electron in the plasma

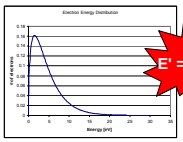
(how do we determine E? →)

q_p = the total excess charge on the particle

ΔV = potential difference (energy lost) between the plasma and substrate due to the plasma sheath

Electrons in a plasma follow a Maxwellian energy distribution

$$f(E) = \frac{2}{\sqrt{\pi}}\left(\frac{1}{T_e}\right)^{\frac{3}{2}} E^{\frac{1}{2}} \exp\left[\frac{-E}{T_e}\right]$$



E' = ~24 eV

Let's only consider the top 0.1 % of electrons in a 3 eV plasma, those are >24 eV and should have enough energy

$$24\,eV = \frac{(q_e)\cdot q_p}{4\pi\varepsilon_0 (15x10-9\,m)} + |(q_e)\cdot 7\,Volts|$$

q_p = -2.8 x10^{-17} Coulombs

which is 177 excess electrons

Electric Field in the Sheath (2)

$$\vec{E}_{sheath} = \frac{V_{plasma} - V_{floating}}{7\lambda_D}$$

Standard macroscopic sheath in a plasma at floating potential

Where λ_d is the Debye length. Thus, the macroscopic electric field is:

$$\vec{E}_{sheath} = \frac{0-(-10)\ volts}{2.8x10^{-4}\,meters} = 3.6x10^4\,\frac{V}{m}$$

At Floating Potential

If we negatively bias the substrate, we can enhance the electric field in the sheath region as follows:

$$\vec{E}_{sheath} = \frac{0-(-100)\ volts}{2.8x10^{-4}\,meters} = 3.6x10^5\,\frac{V}{m}$$

Biased

Thus, by applying a large negative bias to the substrate, we can enhance the electric field in the sheath region

Plasma Charging (Removal Time)

$$\Gamma_e = \frac{1}{4} n_e v_{E'} \exp\left[\frac{-eq_p(t)}{\frac{4\pi\varepsilon_0 r_p}{k_B T_{E'}}}\right]$$

Flux of electrons to the particle

Assuming the worst case scenario to add the 177th electron, the flux is then:

$$\Gamma_e = 3.7x10^{19}\,\frac{electrons}{m^{-2}s}$$

Given a 30 nm particle, the particle charges to it's maximum in 7 milliseconds or less with this approximation

Removal Mechanism

$$\vec{F}_{repulsive} = 177|q|\cdot 3.6x10^5\,\frac{V}{m}$$

Thus, $F_{repulsive}$ = 1.0x10^{-11} Newtons

Is $F_{repulsive}$ greater than F_{vdw} ?

(1) F_{vdw} is in a range of values. [1]Flanagan and Goree quoted 10^{-12} N.

(2) Our electric field model is macroscopic. Some theories suggest an exponential or power law variation especially in regions close to the biased wall. An exponential sheath model yields an electric field of at least 2.6 x10^6 V/m

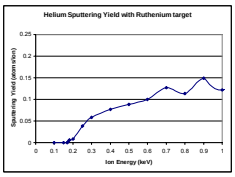
(3) This formulation was considered only for electrons of 24 eV. There is a significant portion of the electron distribution above this threshold especially if there is a two temperature distribution in the plasma, leading to more charging of the particle than was noted above.

(4) The plasma interactions with the sample as well as the particle are not steady-state and the fluctuations of the plasma cause variations in the electric field and the particle charge, both which can enhance the removal mechanism.

[1]Flanagan, T. and J Goree "Dust Release From Surfaces Exposed to Plasma"

Damage Mitigation

Tests are done using a Helium plasma. The sputtering yield of He^+ on Ru is shown below.



- Sputtering threshold of Ru with He ions is ~170 eV.
- As long as we keep the negative bias below the sputtering threshold, there should be no removal of the Ru capping layer

Removal Results

Control Sample 1.5 % ± 0.8 % covered

Processed Sample 0. 16 % ± 0.007 % covered

After 10 minutes of cleaning, we have a particle coverage reduction of 90 %

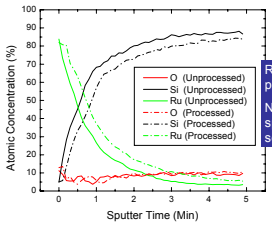
Sample Material	PRE (30nm, 80 nm, 220 nm PSL)
Silicon	82.5 %
Quartz (1/4" thick)	73 %
Ru capped quartz (2.5nm Ru/100nm Si/quartz)	90 %

Cleaning may be much better – dust from not being in a clean room is also counted !

Damage Mitigation Analysis

Sample Stays Smooth !

Auger Electron Spectroscopy

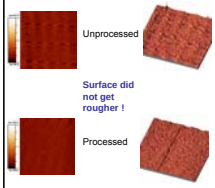


Ru still present !

No sputtering seen !

- The two profiles are almost the same ~ 2.5 nm Ru is still on the top surface.
- Considering there is only 2.5 nm of Ru, seeing the Ru signal is encouraging and shows we did not remove the thin Ru capping layer

Atomic Force Microscopy



Position	RMS Roughness [nm]	
	Unprocessed	Processed
0	0.490	0.521
1	0.525	0.536
2	0.528	0.435
3	1.272	0.436
4	0.897	0.379
Average	**0.742**	**0.461**

The RMS roughness (5μ by 5μ) of the processed sample is clearly smaller than the unprocessed sample. However, there are a few islands on the surface as seen in 3-D pictures, which might possibly be dust on the unprocessed sample. The actual film surface of the processed sample became smoother than the unprocessed sample, which indicates that we cleaned the dust off of the surface while processing these samples using the PACE technique.

Plasma **A**ssisted **C**leaning by **E**lectrostatics

P A C E

The PACE chamber is equipped with a commercial M0RI plasma source and auto-matching network to provide a high-electron dense plasma.

Acknowledgements

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