EUV Mask Production and Cleaning

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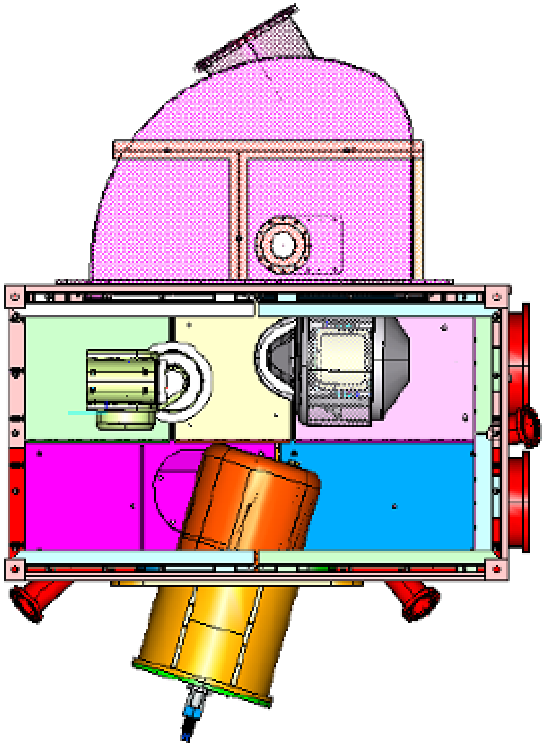
- Brief overview of mask production
- Current particle removal techniques
- New cleaning idea -- PACMAN
  - Metastables provide the energy, electric field allows removal
- Experimental Setup
- Theory and experiments
- Results and conclusions

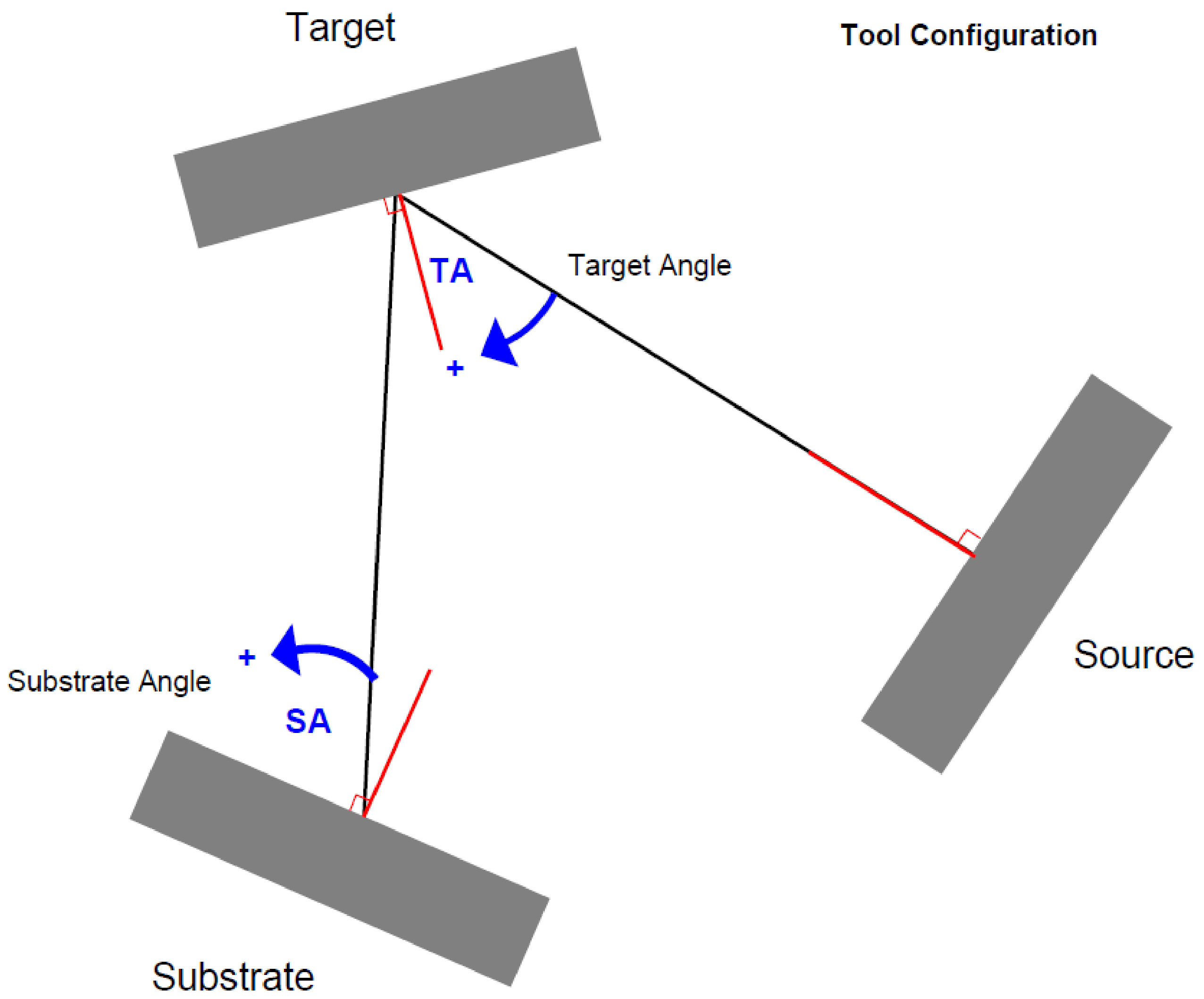
How Masks are Made

Semetach/Veeco tool:

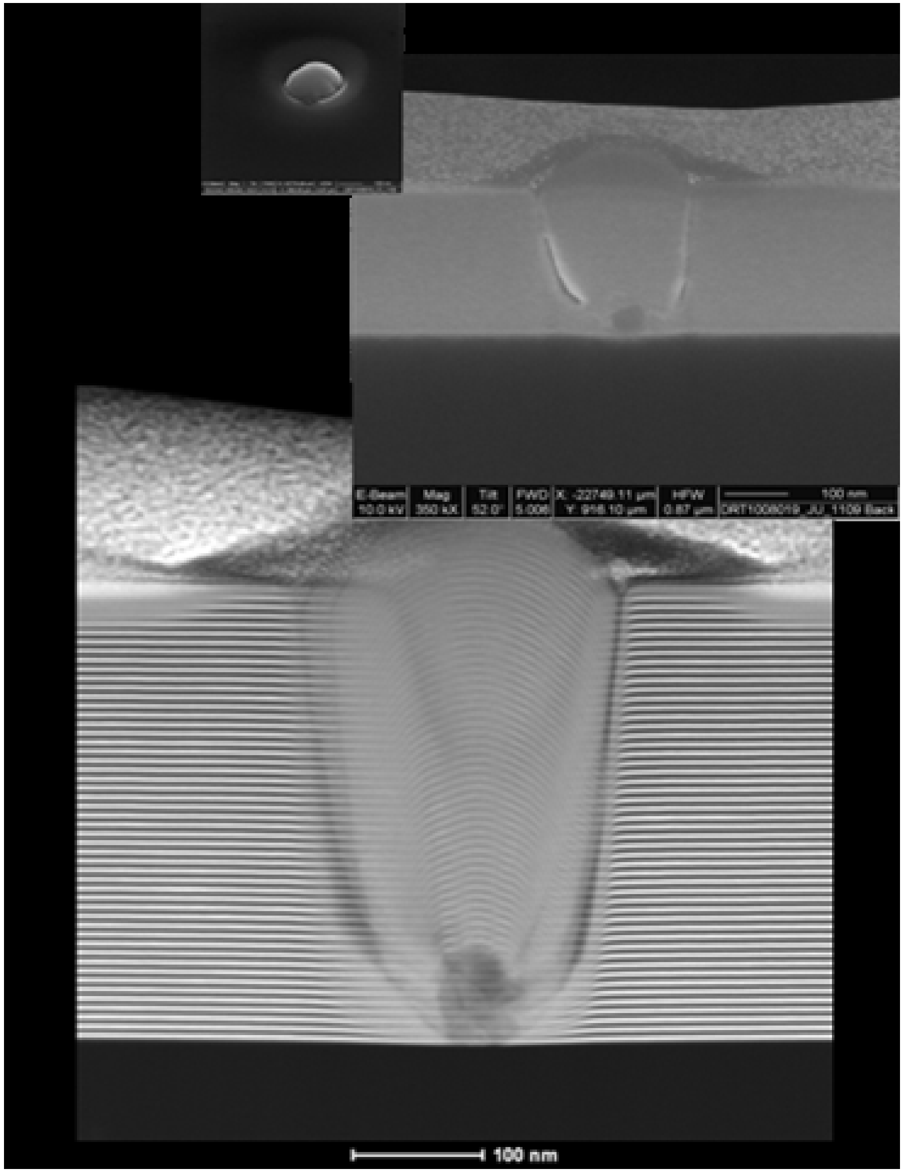
Si and Mo bilayers made by ion beam sputtering



Tool Configuration



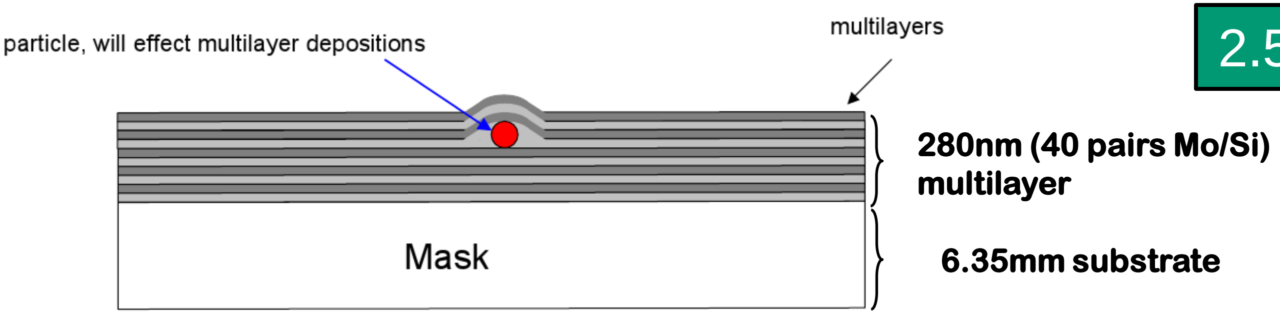
The Danger of Particles During Production



- A particle early on creates a ripple effect on all subsequent layers which destroys the reflectivity in that location.

- Pits are bad too.

Mask Defects During Fabrication



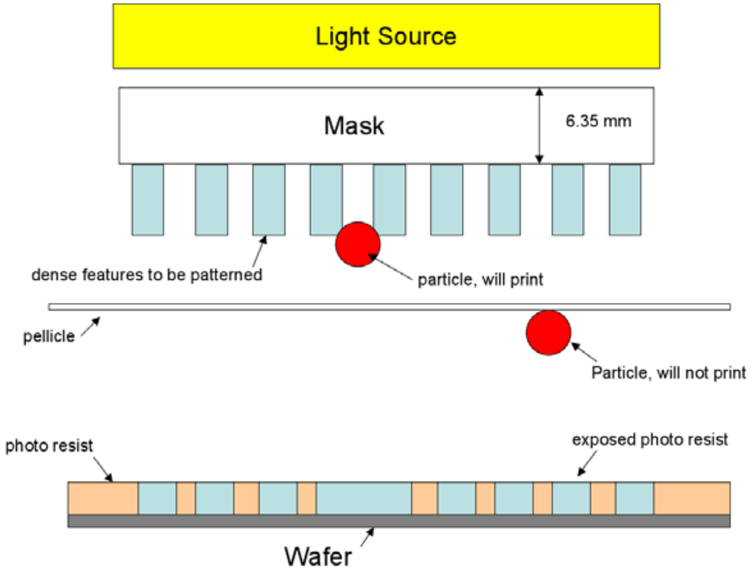
2.5 nm Ru capping layer

Not to scale

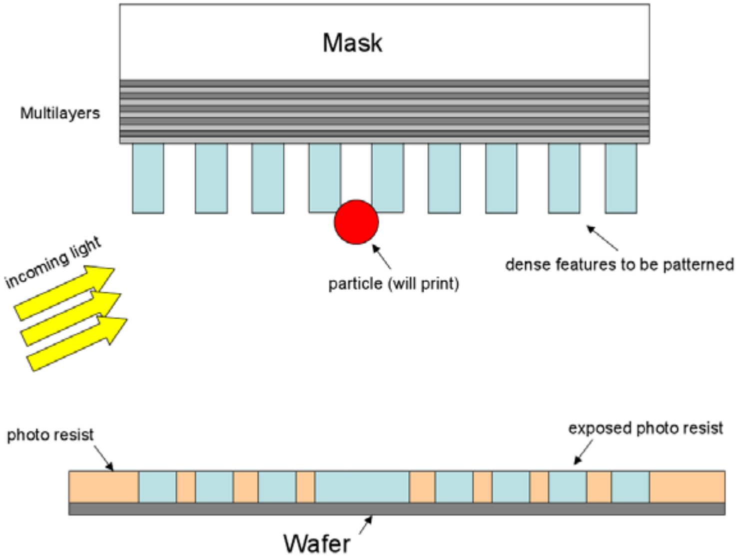
- A particle that falls onto a mask during fabrication that is not cleaned will lead to multilayer defects
  - This will cause printability errors
- High-energy photons will lead to hydro-carbon/carbon layer buildup on the optics material
  - This will reduce the lifetime of the optics material

H. Shin, JR Sporre, R. Raju, and DN Ruzic. Reflectivity degradation of grazing-incident EUV mirrors by EUV exposure and carbon contamination. *Microelectronic Engineering*, 86(1):99–105, 2009.

After Production Mask Cleanliness



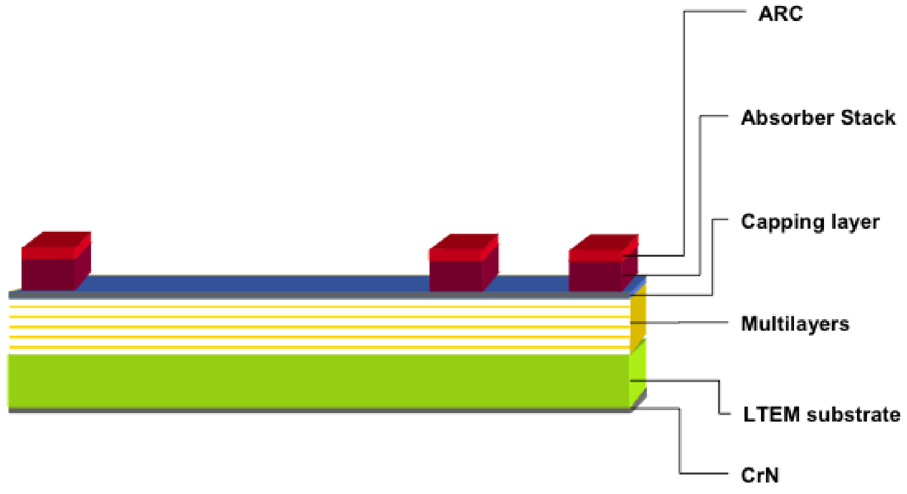
Optical Lithography (image not to scale)



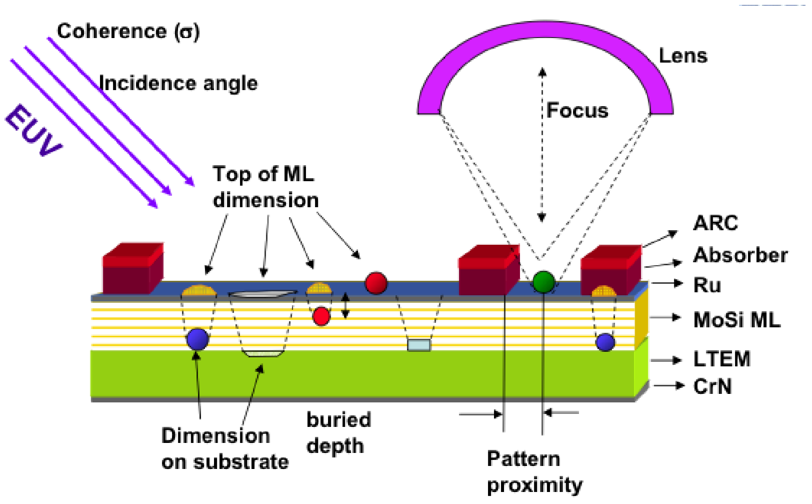
EUV Lithography (image not to scale)

- Mask cleanliness is key
  - Pellicle for optical lithography is not transmissive to EUV
  - Particle defects on EUV masks will print

Mask Structure to Clean



Multilayer EUV Mask Layout



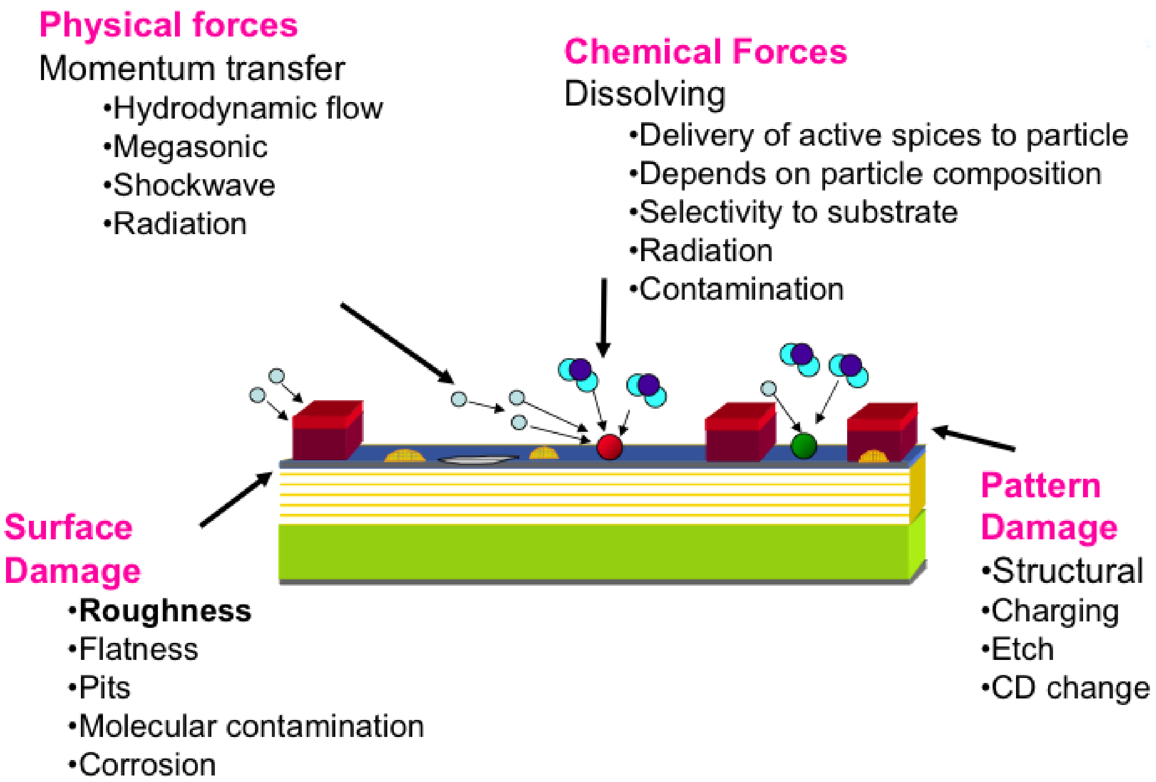
Defects in an EUV Mask

- Only particles on top of the mask can be cleaned
  - Buried defects must be removed during mask fabrication
  - Cleaning must not cause damage
- Particulate contamination is composed of organics and inorganics from handling, machinery movement, and environment

Adapted from A. Rastegar. Particle removal challenges with EUV patterned masks for the sub-22 nm HP node. Proceedings of SPIE, 2010.

Current Removal Techniques

- Point by Point
- Laser-Induced Shockwave Cleaning
- Carbon Dioxide (CO$_2$) Snow Cleaning
- Wet Cleaning



Physical forces

Momentum transfer

- Hydrodynamic flow
- Megasonic
- Shockwave
- Radiation

Chemical Forces

Dissolving

- Delivery of active spices to particle
- Depends on particle composition
- Selectivity to substrate
- Radiation
- Contamination

Surface Damage

- **Roughness**
- Flatness
- Pits
- Molecular contamination
- Corrosion

Pattern Damage

- Structural
- Charging
- Etch
- CD change

- Mega-sonic / Cavitation Cleaning

Adapted from A. Rastegar. Particle removal challenges with EUV patterned masks for the sub-22 nm HP node. Proceedings of SPIE, 2010.

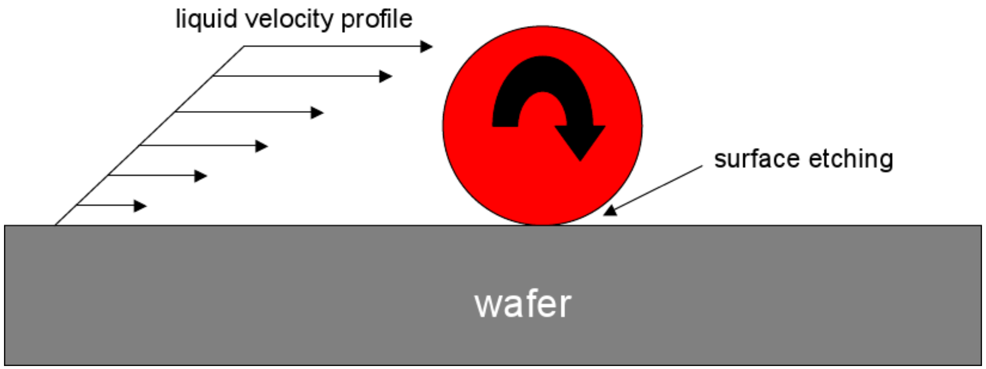
More on each of these in the next few slides

Current Particle Removal: Point by Point

- Inspection
  - Mask inspection tool
  - Scanning electron microscopy (SEM)
- Particle removal
  - Adaption of an atomic force microscope (AFM)
  - Other physical means
- Re-inspection

Slow and out-dated technology!

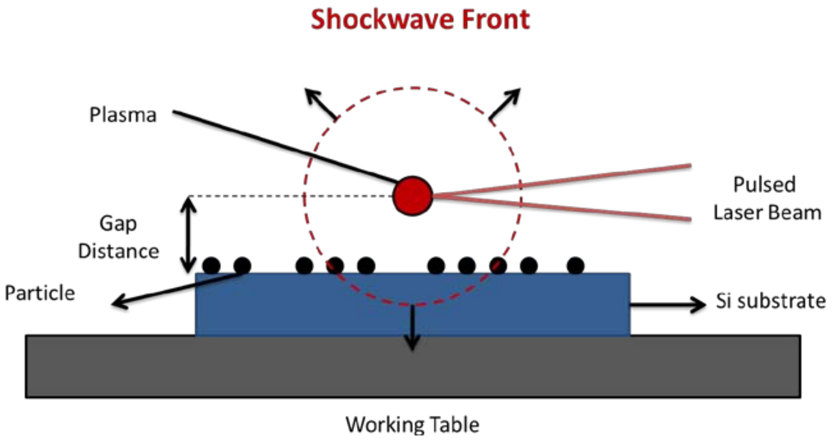
Wet & Megasonic/Cavitation

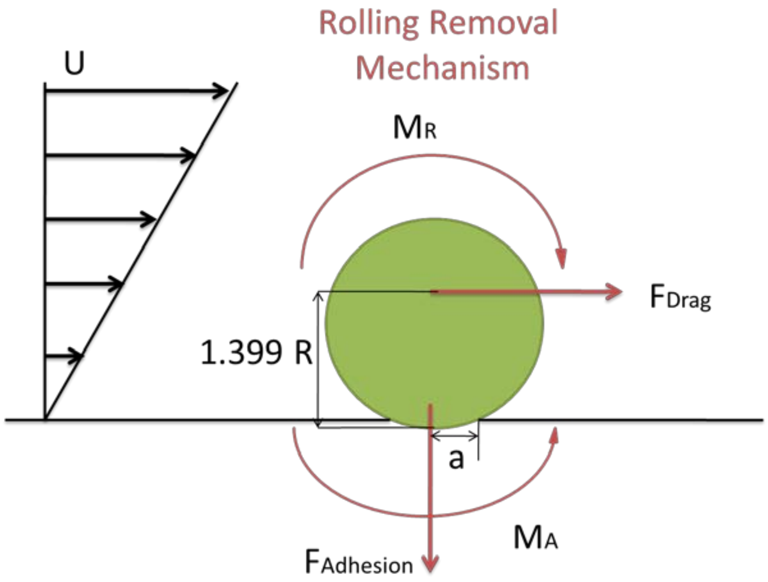


- Uses SC1
  - Sulfuric acid and hydrogen peroxide mixture
- Wash solution over surface
  - Surface etching under particle occurs
  - Velocity of liquid “rolls” particle away
    - Brush scrubbing system can be used as well
- Chemicals used are usually contaminated at the size of the particulate being removed for EUV
- Add megasonic vibration to aid cleaning

Laser-Induced Shockwave Cleaning

- A laser is focused over the surface to be cleaned
- Shockwave creates a pressure wave that interacts with the particle
- Particle is rolled off of the surface





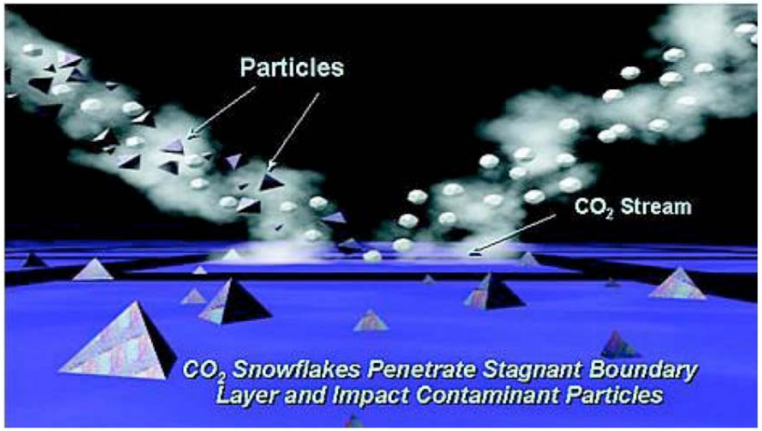
Shockwave can cause damage!

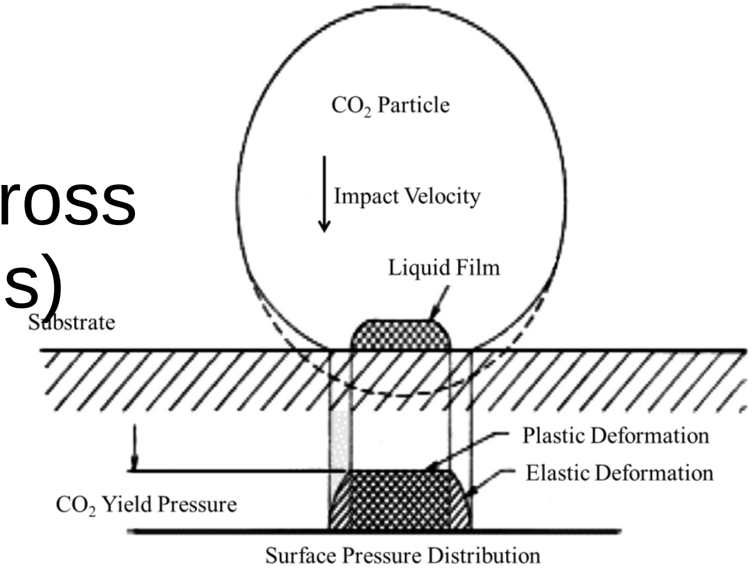
J.M. Lee, S.Y. You, J.G. Park, and A.A. Busnaina. Laser Shock Cleaning for Particle Removal. Semiconductor International, 2003.

Carbon Dioxide (CO_2) Snow

- Uses a stream of small CO_2 particles
- Momentum transfer to clean inorganics
- Solvent process to clean organics
- Stream must be scanned across surface (size of stream varies)

Only area cleaned is in the path of the CO_2 stream!





R. Sherman. Carbon Dioxide Snow Cleaning. Particulate Science and Technology, 25(1), 2007.

W.V. Brandt. Cleaning of Photomask Substrates Using CO2 Snow. 21st Annual BACUS Symposium on Photomask Technology,Proc. of SPIE, 2003.

Current Industry Standard Cleaning

VUV (173 nm) → Ozone with APM/SPM → APM & Megasonics → DI rinse → Spin Dry

- Vacuum ultraviolet light
  - Creates hydrophilic surface for chemical wetting
- Ozonated water with ammonia peroxide mix (APM) and sulfuric peroxide mix (SPM)
- APM and megasonic
- DI rinse
- Spin Dry

Insufficient and outdated techniques that may not be extendable to EUV masks!

Adapted from: A. Rastegar. Particle removal challenges with EUV patterned masks for the sub-22 nm HP node. Proceedings of SPIE, 2010.

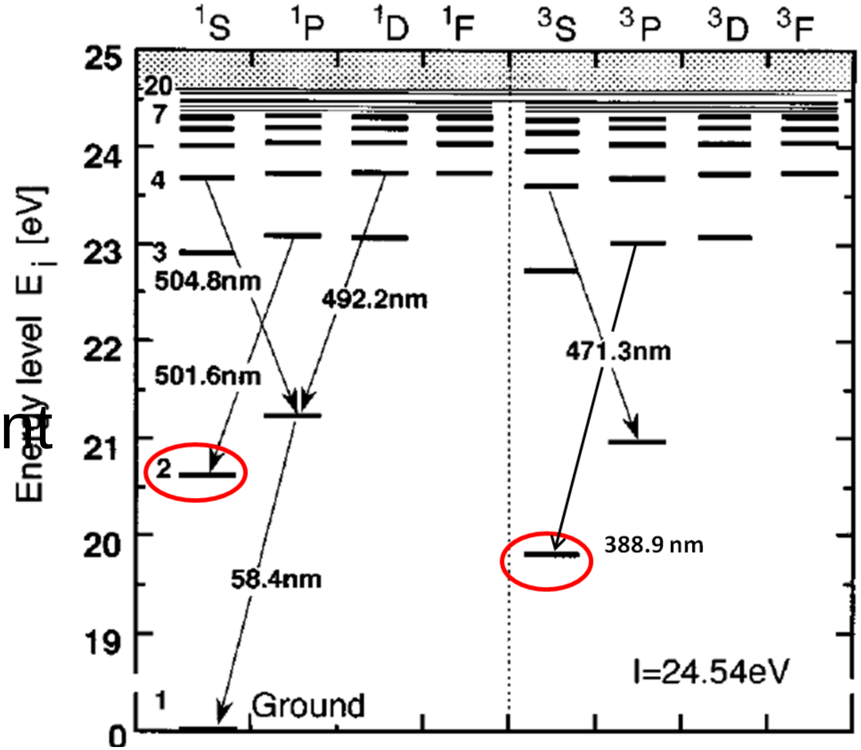
New Cleaning Idea: Metastable Helium Cleaning

- **P**lasma **A**ssisted-**C**leaning by **M**etastable-**A**tom **N**eutralization (PACMAN)
- Uses helium metastables to clean hydrocarbon contaminants
  - Metastable helium is neutral particle
- Plasma-based cleaning technique
  - Compatible with EUV Lithography
    - Vacuum based
  - Can be used as an intermediate step in chip making process

Patent applied for Fall 2008 by UIUC

Metastables

- What is a metastable?
  - Quantum mechanically stuck
    - ($\Delta l \neq 0$)
  - Neutral particle
  - Internal energy
    - (1s2s not 1s^2)
- Capable of transferring significant amount of energy (19.820 eV and 20.616 eV)
- Found in plasma but relatively short lived



S. Sasaki, S. Takamura, S. Watanabe, S. Masuzaki, T. Kato, and K. Kadota, "Helium I Line Intensity Ratios in a Plasma for the Diagnostics of Fusion Edge Plasmas," *Rev. Sci. Instruments* **67**(10), 1996.

- Metastables diffuse in the same way as other neutral gas atoms in the plasma
- Triplet and singlet nomenclature arises from spin quantization

Metastables

- Why use Helium?
  - ☐ Chemically inert (noble gas)
  - ☐ High energy →
  - ☐ Low Z material
  - ☐ Long metastable lifetime of 4.2 x 10^3 seconds
- Argon and Neon are potentially useful, but higher Z means higher damage from sputtering!

Species	Energy [eV]	Lifetime [s]
Helium (singlet)	20.616	2.0 x 10^{-2}
Helium (triplet)	19.820	4,200
Neon	16.616	24.4
Argon	11.548	55.9

Table of energy levels and lifetimes for metastables

W. Sesselmann, B. Woratschek, J. Kuppers, G. Ertl, and H. Haberland, "Interaction of metastable noble-gas atoms with transition-metal surfaces: Resonance ionization and Auger neutralization," *Physical Review B* **35**(4), pp. 1547–1559, 1987.

Metastables

- Metastables transfer energy through Auger de-excitation
  - He* + (S) → He + (S-) + e-
- As the metastable interacts wi the particles, an electron from the surface fills the 1s hole in t He, and the 2s electron is ejected from the He
- If a metastable “steals” a bonc electron, the surface from whic it is stolen is weakened

Metastables create broken bonds (i.e. “holes”) in the surface being cleaned!

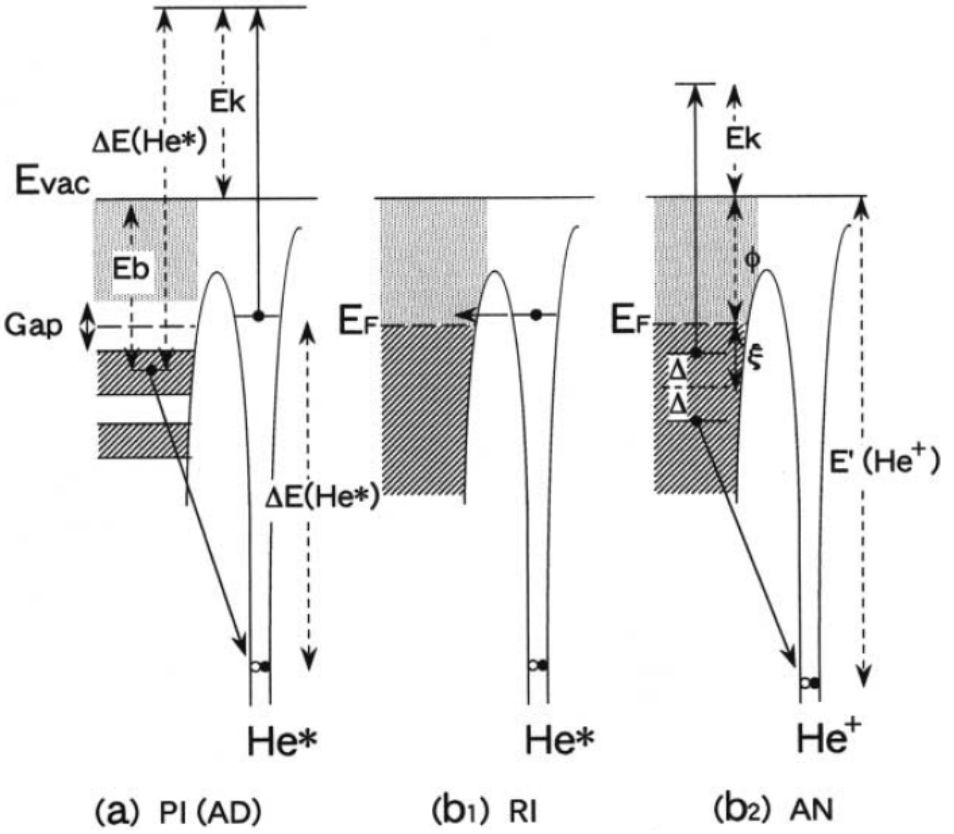
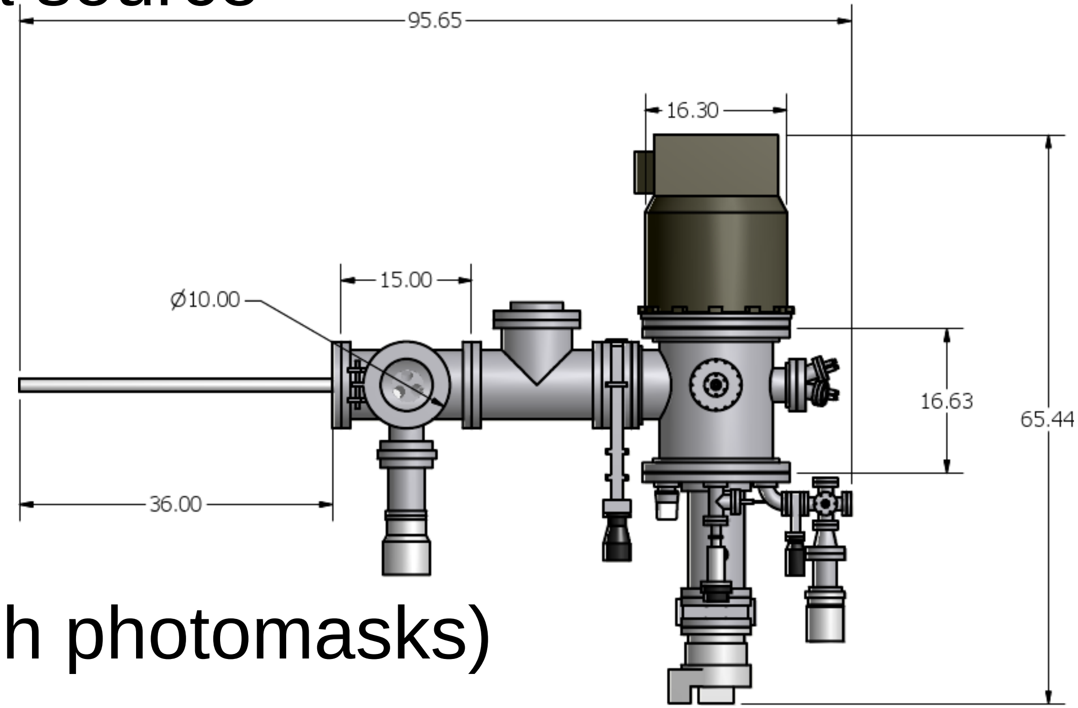


Diagram of the energy transfer mechanism for metastables to a surface. Image from Ueno et. al.

N. Ueno, H. Yasufuku, S. Kera, K. Okudaira, and Y. Harada, “Surface Imaging Using Electrons Excited by Metastable-Atom Impacts,” *Lecture Notes in PHysics - New York then Berlin* , pp. 131–144, 2002.

Experimental Setup

- m=0 helicon plasma source
- DC substrate bias that is either steady-state or pulsed
- Capable of processing full sized (6 inch x 6 inch photomasks) or 150 mm wafers



- Coupled to a class 100 laminar flow clean hood
- Helium is used as the process gas for the cleaning technique

Experimental Setup: Test Materials

- Test particle is polystyrene latex nanoparticles (PSL)
  - Chemical formula C_8H_8
  - Obtained from Duke Scientific in aqueous solution
- Test surfaces are silicon wafers
  - Silicon wafers from Addison Engineering
    - 25 mm diameter
    - 1-10 Ω-cm
    - N type (phosphorus doped)

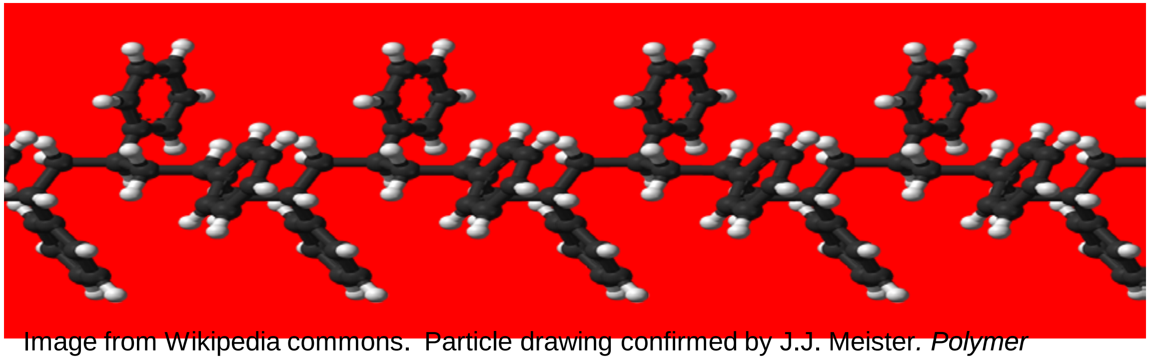
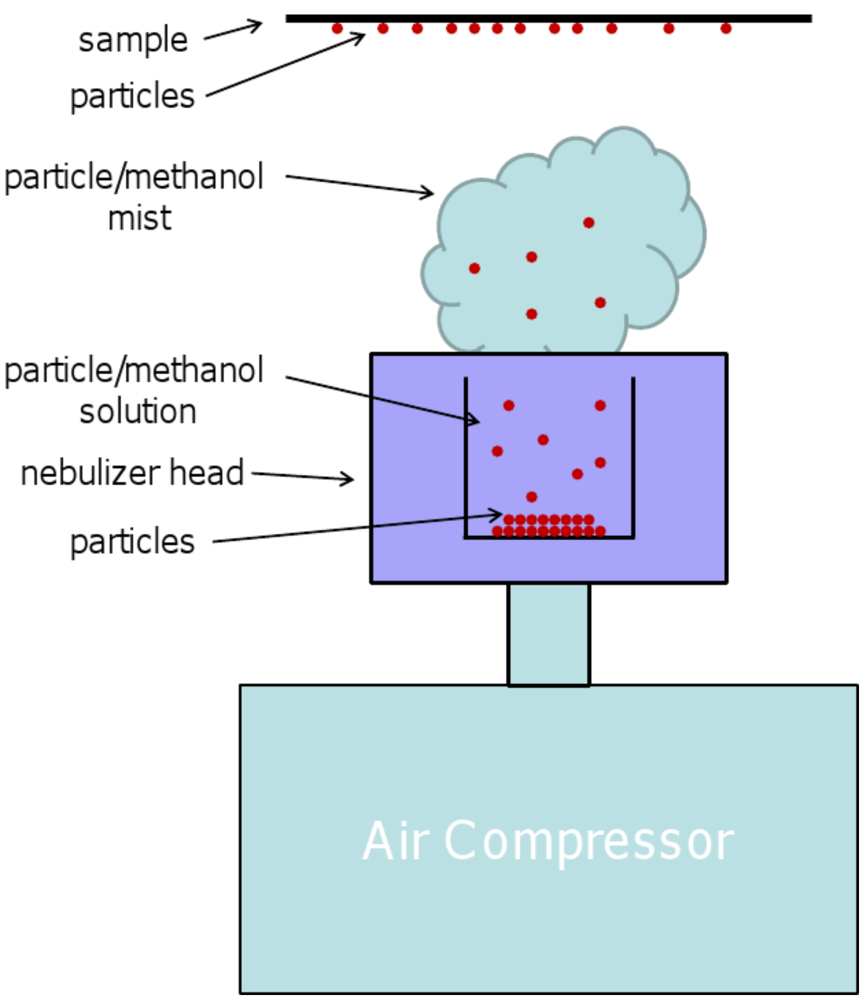


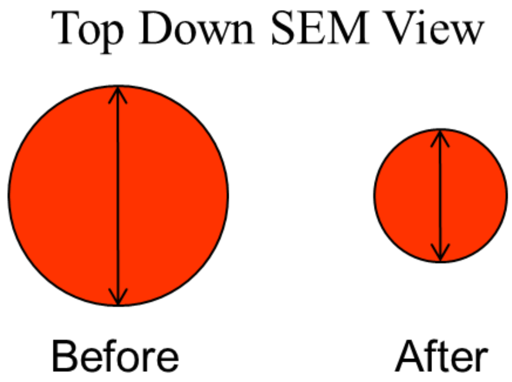
Image from Wikipedia commons. Particle drawing confirmed by J.J. Meister. *Polymer modification: principles, techniques, and applications*. CRC Press, 2000.

Particles & Deposition

- Particles obtained in water solution
- Diluted with methanol
  - Quicker drying
- Solution placed within a nebulizer
- Particle/methanol mist is directed at the wafer
  - Methanol evaporates, particles remain



Particle Measurement



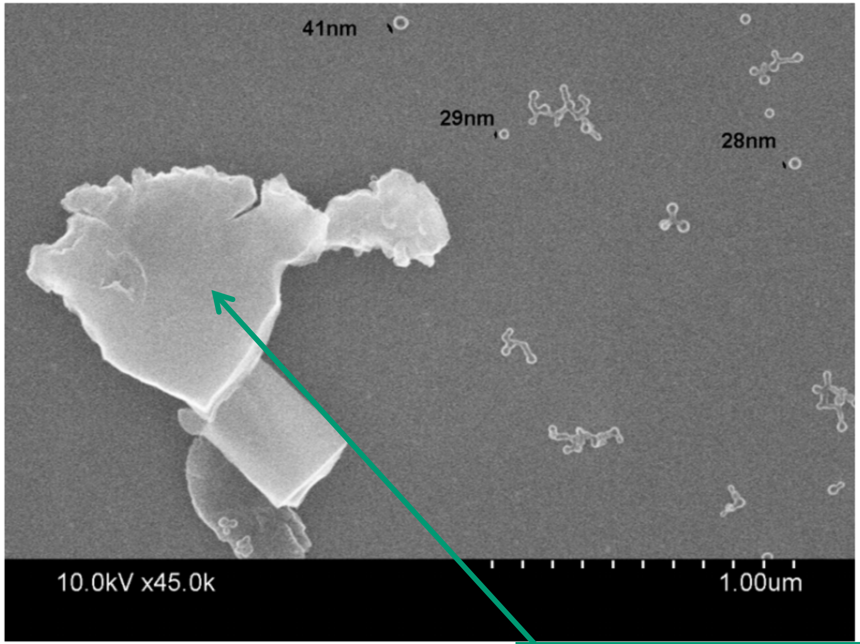
Removal Rate Determination

(1) Measure the number of pixels before and after
(2) Convert the number of pixels to length
(3) Calculate the volume of the particle before & after
(4) Calculate the error on the volume calculation

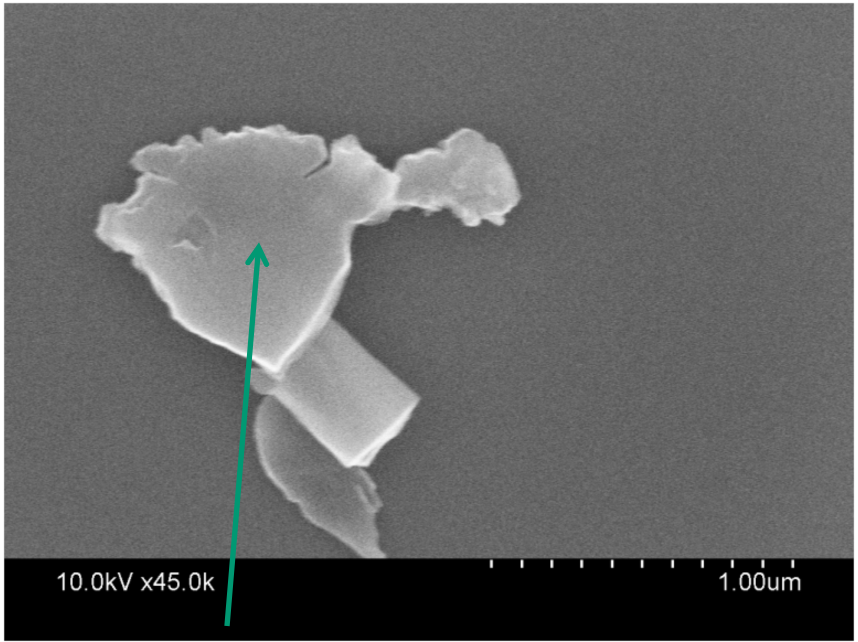
$$\text{Removal Rate} = \frac{V_{\text{before}} - V_{\text{after}}}{\text{processing time}}$$

- Particles measured top down via SEM
  - Same particles before and after at the same magnification
  - Measurement error 1 pixel (~10.0 nm/pixel)
    - Pixels measured using GNU Image Manipulation Program (GIMP)
- At least 4 particles are measured per sample
- Error computed as the standard deviation of the measurement

Initial Removal Results



Before

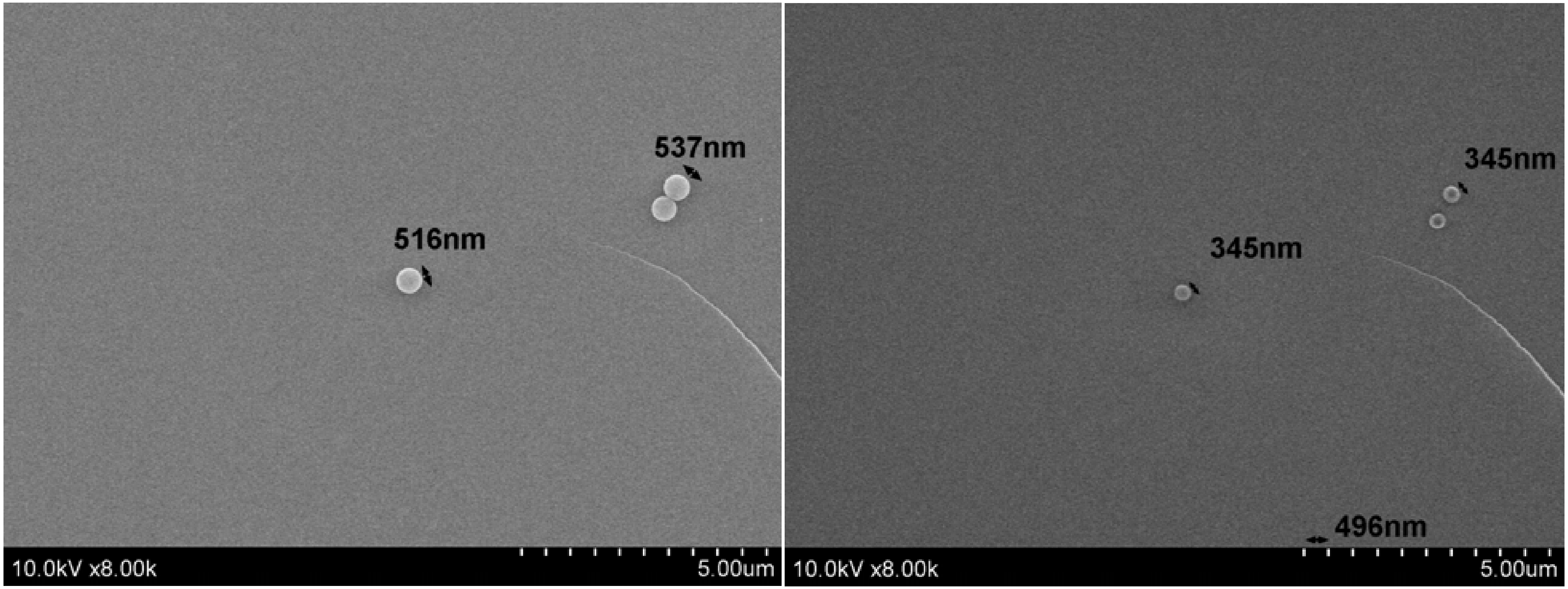


After

particle from wafer “marking”
NOT polystyrene latex particle

- 30 nm – 220 nm PSL particles can be removed in 10 minutes processing
  - No detectable residual contamination
- Switch to larger contamination to determine removal mechanism

Removal in “etching-like” fashion



Before After

- Particles are not removed all at once
  - Particles “shrink” in size
  - Centers of the particles remain in the same position so they are not moving

Parameters Relevant to Removal

- Processing Time
- Ion Flux
- Electric Field
- Electron Flux
- Metastables
- Temperature

Parametric Approach:

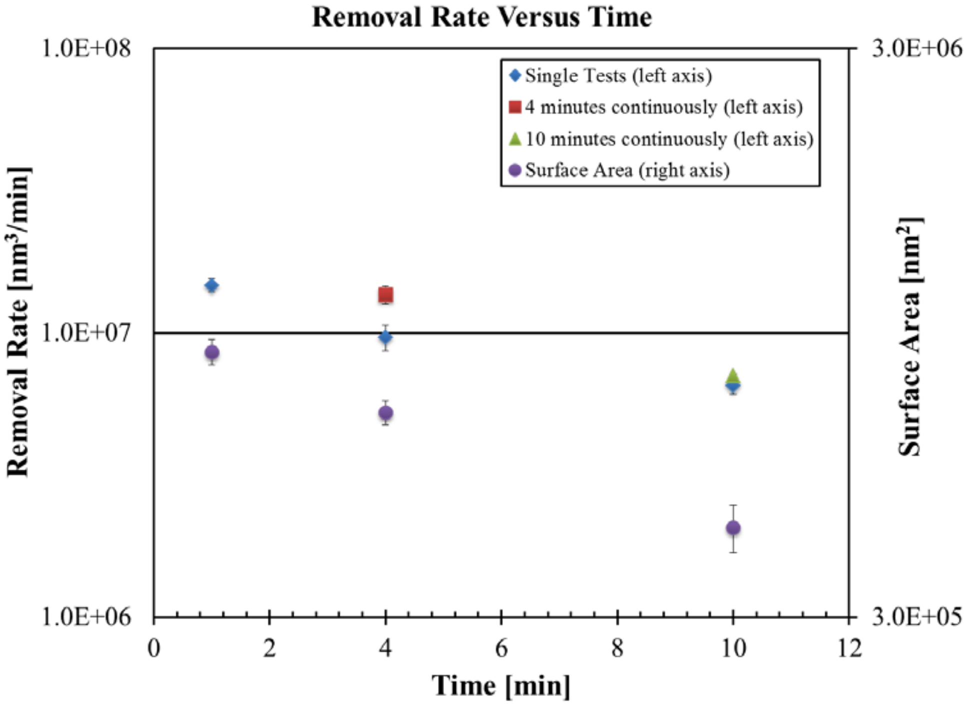
(1) Systematically eliminate parameter to understand its effect

(2) Understand theory behind the physical parameter changed

(3) Use understanding from theory to predict the next removal experiment

Processing Time

- Single tests were run at 1 minute intervals with an air interval of at least 5 minutes between experiments
- Two tests were run continuously for 4 and 10 minutes
  - Experiments measured at 4 minutes show small deviation
    - Attributed to sample differences
  - Experiments at 10 minutes show no difference



Horizontal error is the size of the data marker

Observation: Removal rate decreases with processing time

Conclusion: Change in some flux to the particle affects removal rate

Plasma conditions: 2 kW plasma, 10 mTorr He, 100 SCCM

Parameters Relevant to Removal

- Processing Time ✔
- Ion Flux
- Electric Field
- Electron Flux
- Metastables
- Temperature

Parametric Approach:

(1) Systematically eliminate parameter to understand its effect

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(3) Use understanding from theory to predict the next removal experiment

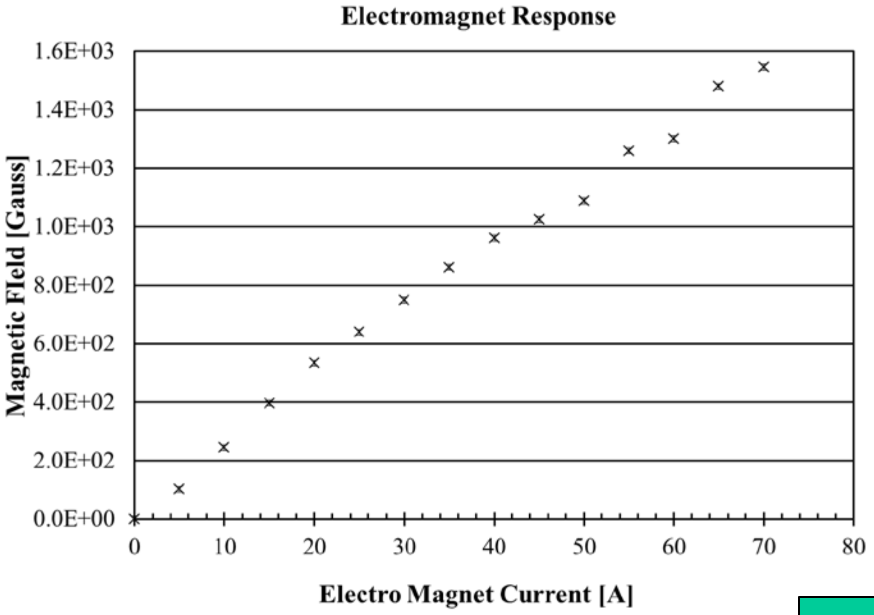
Ion Flux

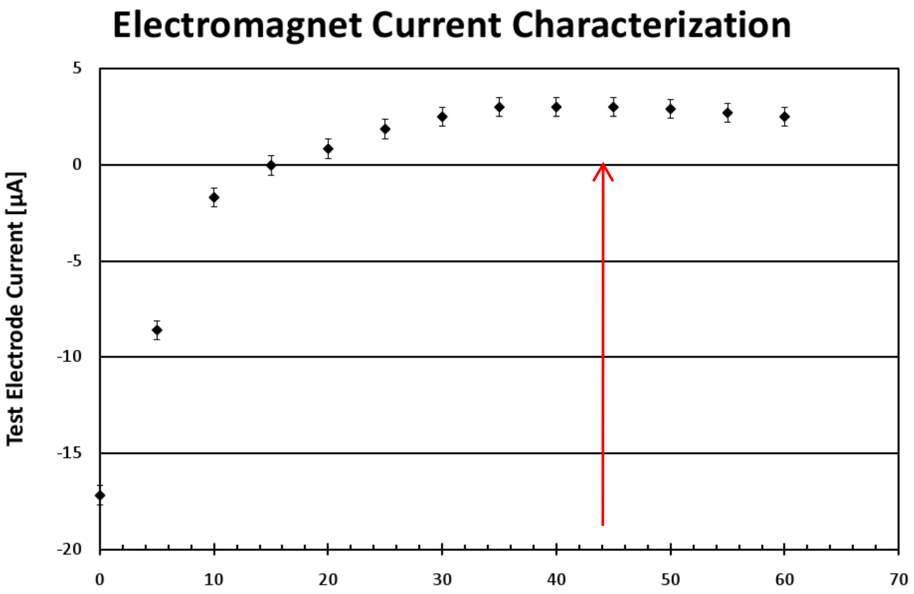
Bias to sample [V]	Ion Energy	Removal Rate [nm³/s]
-69.1 ± 0.5	High-energy	$4.6\times10^6 \pm 1.7\times10^5$
+10/-70 ± 0.1 100 Hz, 90% duty cycle	Intermittent High-energy	$7.1\times10^6 \pm 1.4\times10^5$
+12 ± 0.5	No ions	$1.2\times10^7 \pm 1.1\times10^6$

- Controlling incident ion flux to the sample through application of bias
- 3 experiments
  - High-energy ions only
  - Intermittent high-energy ions
  - No ions
- Eliminating ions leads to better removal

What if one uses just ions and helium metastables?

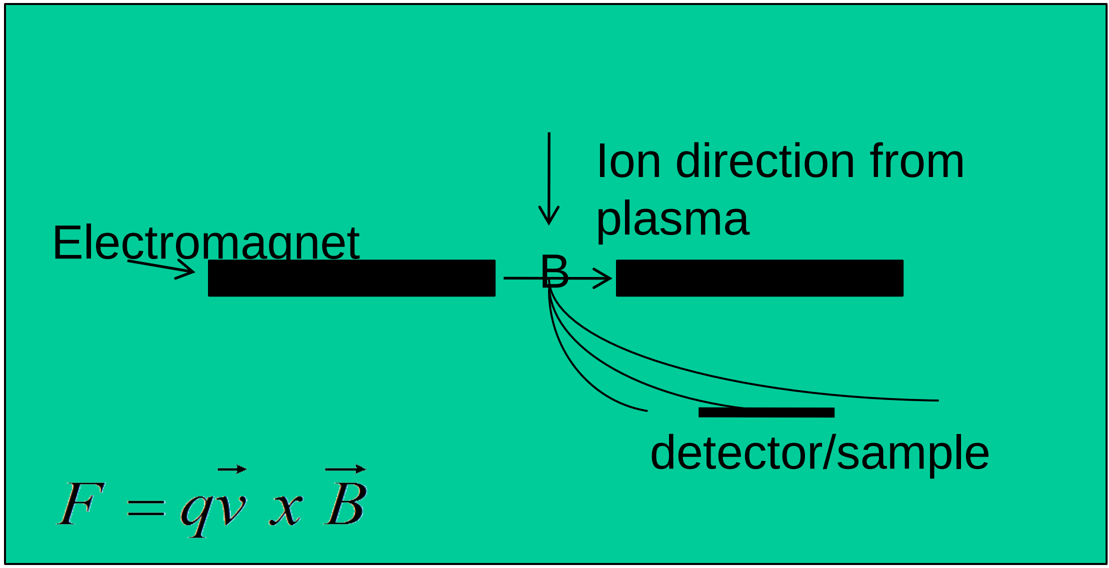
Ions and Metastables





- Just using ions and helium metastables results in negligible removal

Conclusion: Eliminating ions from the sample all together increases the removal rate.



Ion direction from plasma

Electromagnet

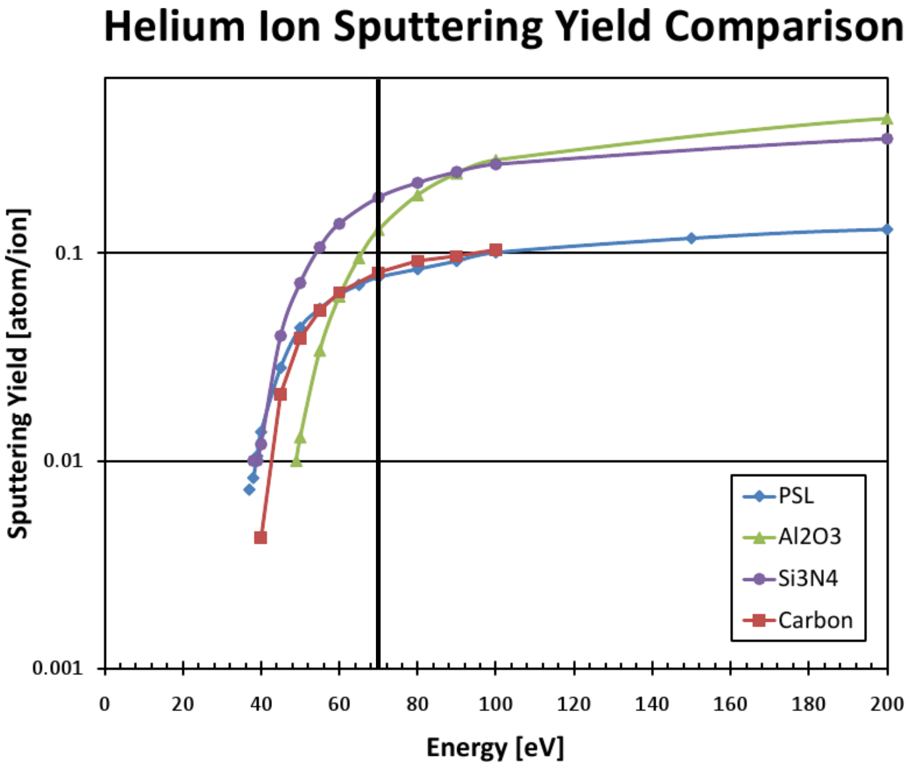
B

detector/sample

$$F = q\vec{v} \ x \ \vec{B}$$

Ion Flux: Theory Development

- Steady DC and pulsed bias tests will have sputtering from 70 V helium ions.
- From SRIM/TRIM the calculated classical sputtering is 0.049 nm/s.
  - ☐ Total of 14.7 nm of PSL removed in steady DC test
  - ☐ Total of 1.47 nm of PSL removed in pulsed bias test
- Removal is from the top of the particle only (ions are directed from plasma sheath).
- Conclusion: Classical sputtering has little effect

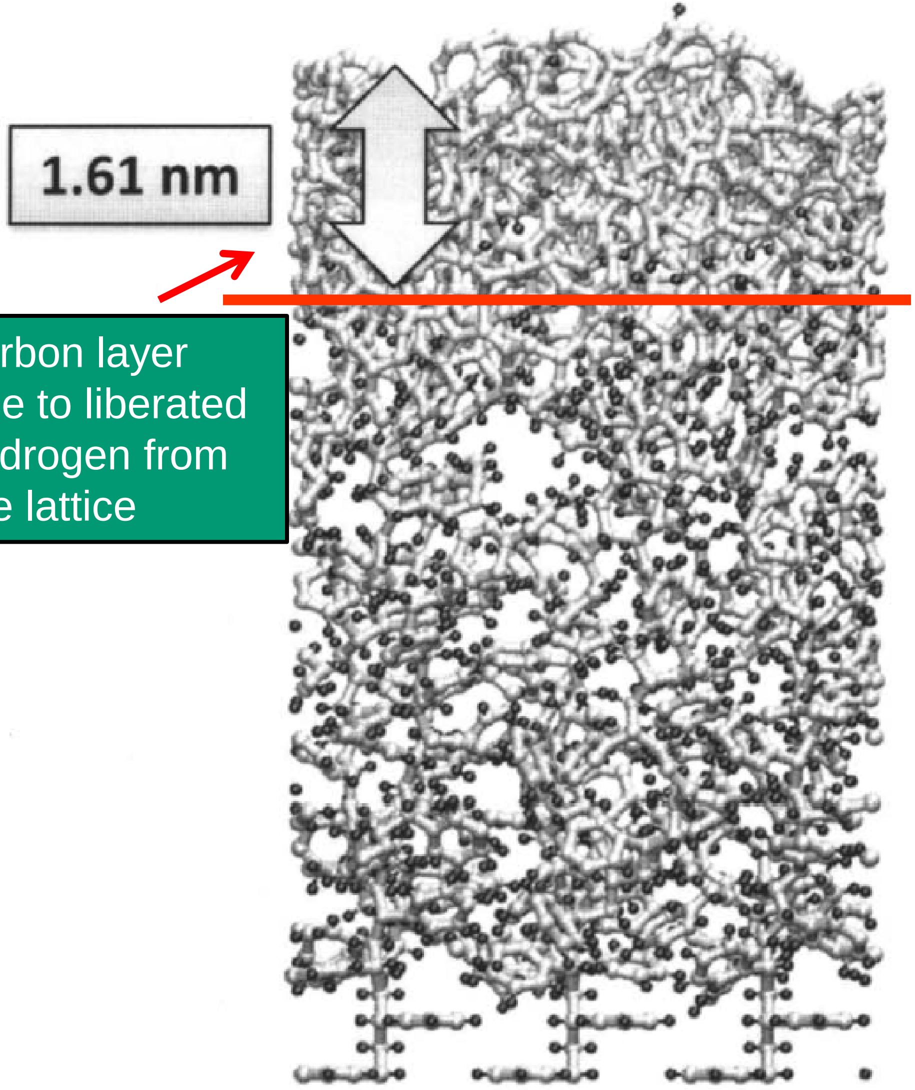


Sputtering yields simulated from SRIM/TRIM.

J. Ziegler, J. Biersack, and M. Ziegler, *SRIM-The stopping and range of ions in matter*, SRIM Co., 2008.

Ion flux prevents continued removal

- High-energy ion bombardment of hydrocarbons (polystyrene) liberates hydrogen from the lattice
- Reduces the surface to a carbon layer
- Further removal of materi through high-energy ion impact slows



carbon layer due to liberated hydrogen from the lattice

R. Bruce, S. Engelmann, T. Lin, T. Kwon, R. Phaneuf, G. Oehrlein, B. Long, C. Willson, J. Végh, D. Nest, *et al.*, "Study of ion and vacuum ultraviolet-induced effects on styrene-and ester-based polymers exposed to argon plasma," *Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures* **27**, p. 1142, 2009.

Results of MD simulation of ~7,800 impacts by 100 eV Ar ions. Image from Bruce et. al.

Parameters Relevant to Removal

- Processing Time ✔
- Ion Flux ✔
- Electric Field
- Electron Flux
- Metastables
- Temperature

Parametric Approach:

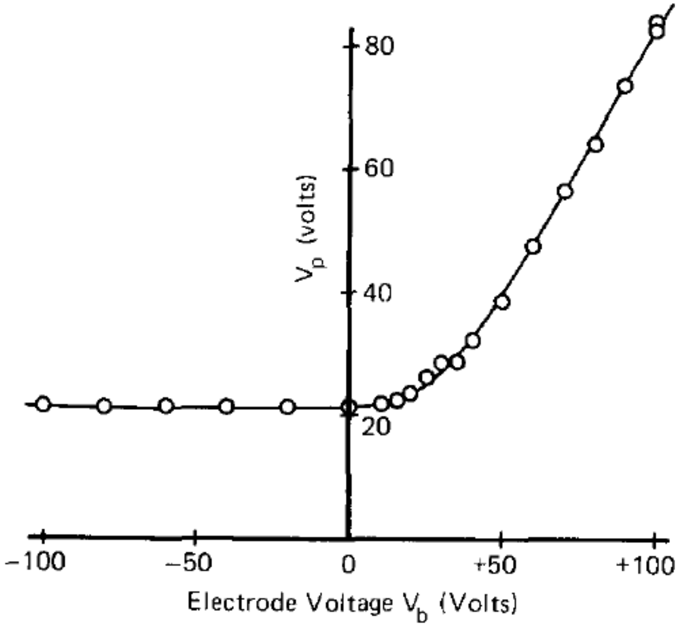
(1) Systematically eliminate parameter to understand its effect

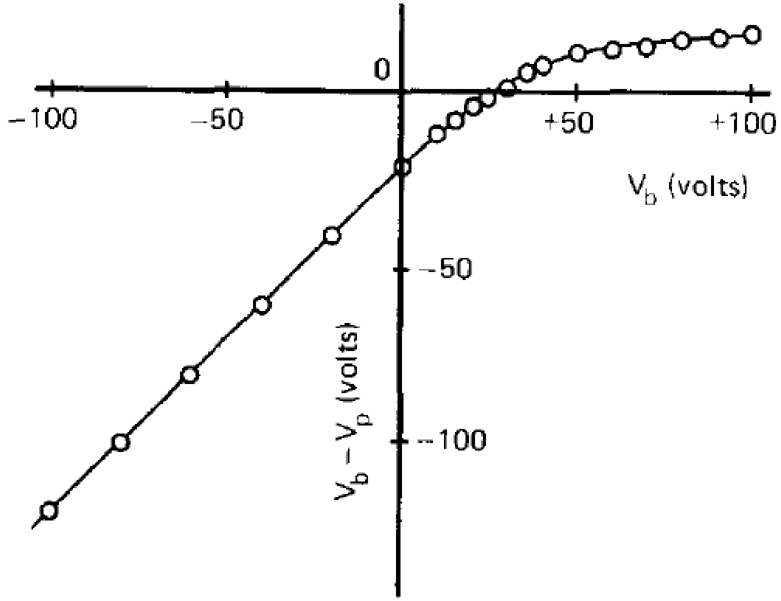
(2) Understand theory behind the physical parameter changed

(3) Use understanding from theory to predict the next removal experiment

Bias

- An electrical bias was used to keep ions from impacting the surface
  - Does the location of where the bias is applied affect removal?
- How does application of bias change the plasma?

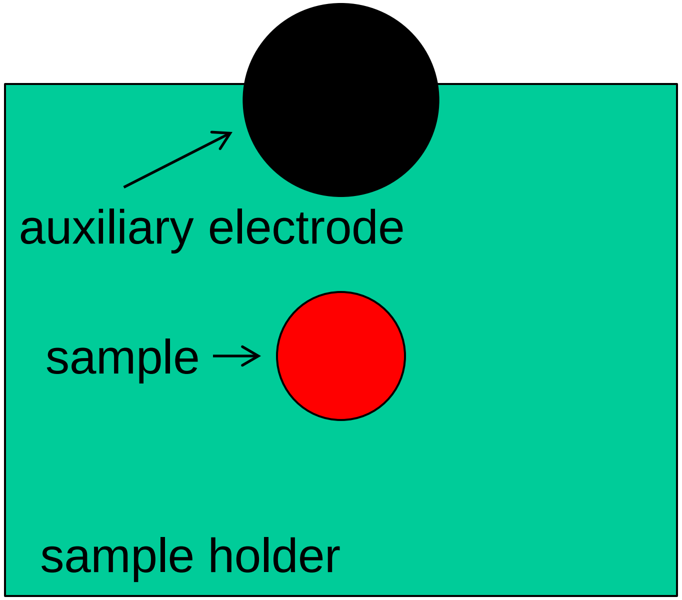


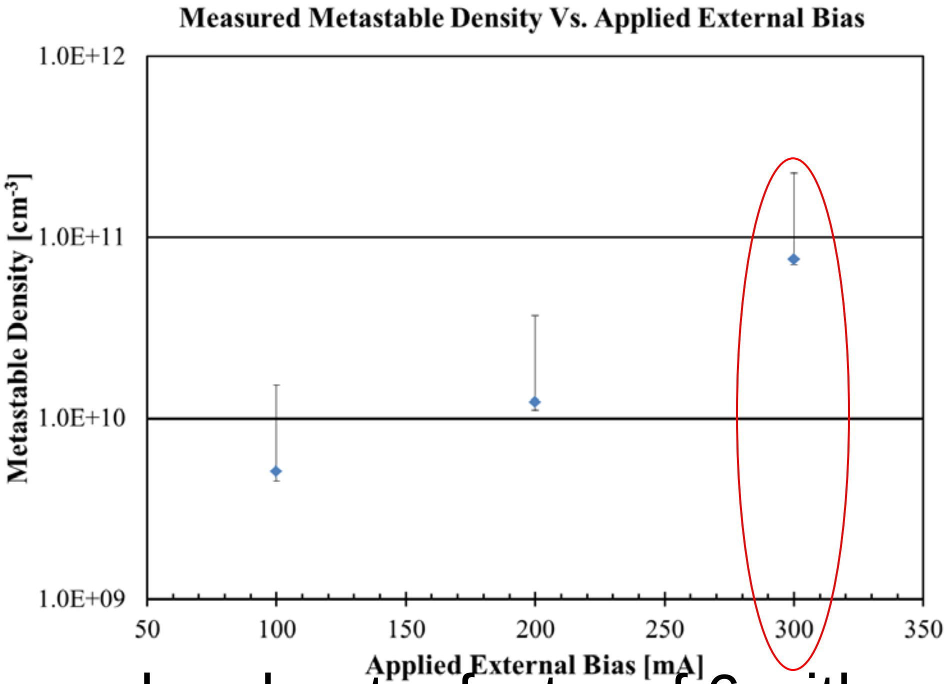


JW Coburn and E. Kay. Positive-ion bombardment of substrates in rf diode glow discharge sputtering. *Journal of Applied Physics*, 43(12):4965–4971, 2009.

Auxiliary Bias

- Auxiliary bias added to copper disc about 3 inches from sample

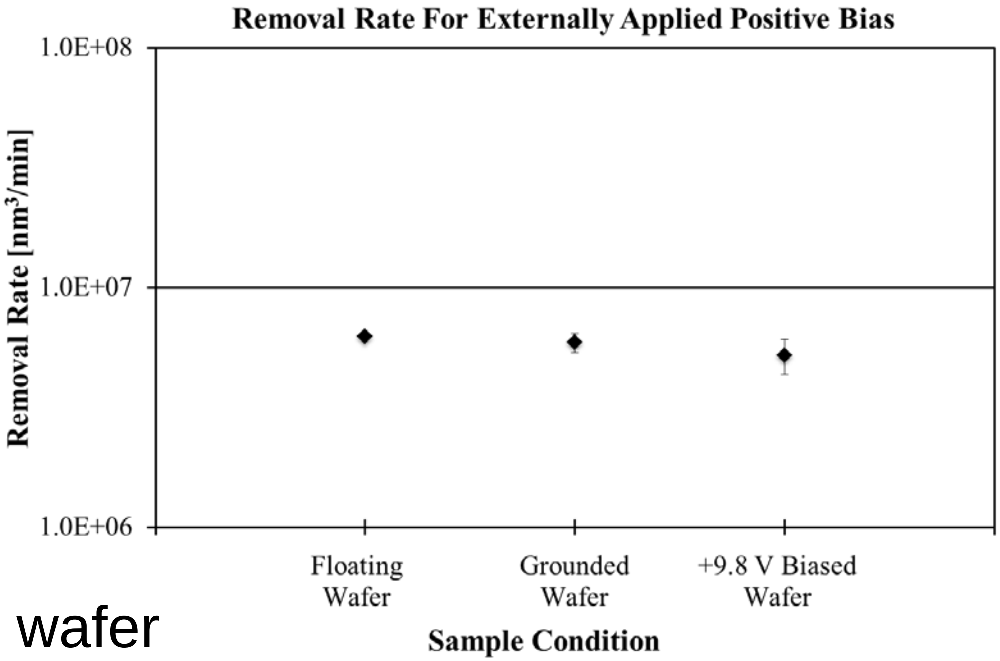




- Metastable density increases by about a factor of 6 with 300 mA external bias

With Aux. Bias: More Metastables, No change in electric field on sample

- +16V, 300±25 mA of current drawn from the plasma for various wafer conditions
  - Applied to copper disc sitting 3 inches from the wafer

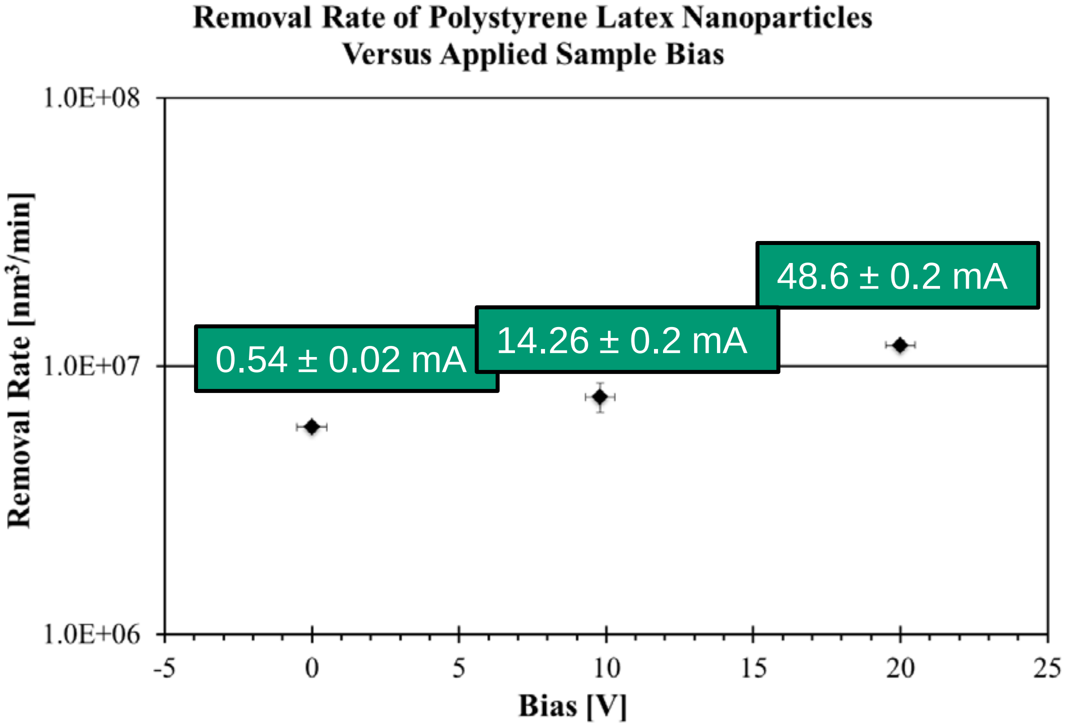


- Removal for floating wafer, grounded wafer, and positively biased wafer relatively steady

Plasma conditions:
2 kW plasma, 10 mTorr He, 100 SCCM

Bias on sample (no metastable increase) increased electric field and electron flux

- Bias of +0 V, +9.8 V, and +20.1 V applied to sample
- As bias to the sample is increased, the removal rate increases



- Application of positive bias changes a key parameter: Electric field in the plasma sheath

Bias: Electric field change

- Electric field in the plasma sheath calculated as:

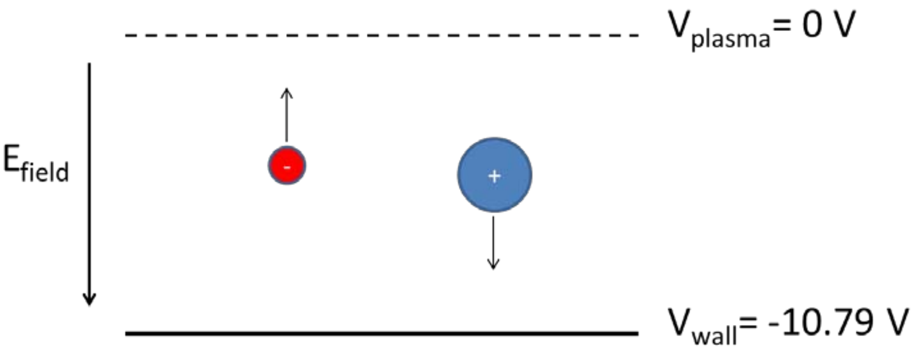
$$E = -2\left(\frac{J_{i,0}}{\epsilon_0}\right)^{1/2}\left(\frac{2e}{m_i}\right)^{-1/4}(|V|)^{1/4}\cdot\mathrm{sign}(V)$$

Bias [V]	$V_{bias} - V_{plasma}$ [V]	Electric Field [V/m]	Removal Rate [nm^3/min]
-69.1	- 79.05± 0.5	$6.2\times10^4 \pm 2\times10^3$	$4.6\times10^6 \pm 4.6\times10^5$
Floating	- 10.79± 0.12	$3.8\times10^4 \pm 5\times10^2$	$4.7\times10^6 \pm 4.4\times10^5$
+ 0	- 8.91±0.58	$2.6\times10^4 \pm 1\times10^3$	$5.9\times10^6 \pm 2.7\times10^5$
+ 9.8	+ 0.80±0.52	$-1.4\times10^4 \pm 3\times10^3$	$7.7\times10^6 \pm 9.5\times10^5$
+ 20.1	+10.15± 0.63	$-2.6\times10^4 \pm 2\times10^3$	$1.2\times10^7 \pm 5.1\times10^5$

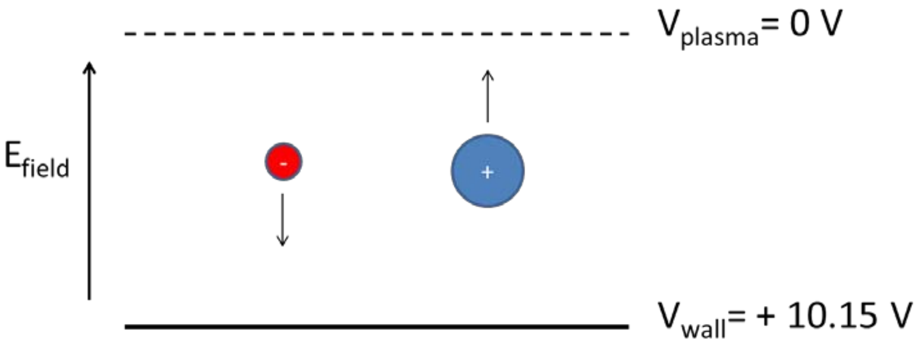
Removal rate increases as electric field points less from the plasma into the surface (less positive, more negative)

Two Effects of Electric Field

- Draws electrons to surface, repels ions
- Creates induced field in particle to keep holes at the surface (keeping bonds near surface broken)



Normal Case



Positive Wall Case

And, biasing positive (with respect to plasma potential) reduces the number of ions hitting the sample!

Parameters Relevant to Removal

- Processing Time ✔
- Ion Flux ✔
- Electric Field ✔
- Electron Flux ✔
- Metastables
- Temperature

Parametric Approach:

(1) Systematically eliminate parameter to understand its effect

(2) Understand theory behind the physical parameter changed

(3) Use understanding from theory to predict the next removal experiment

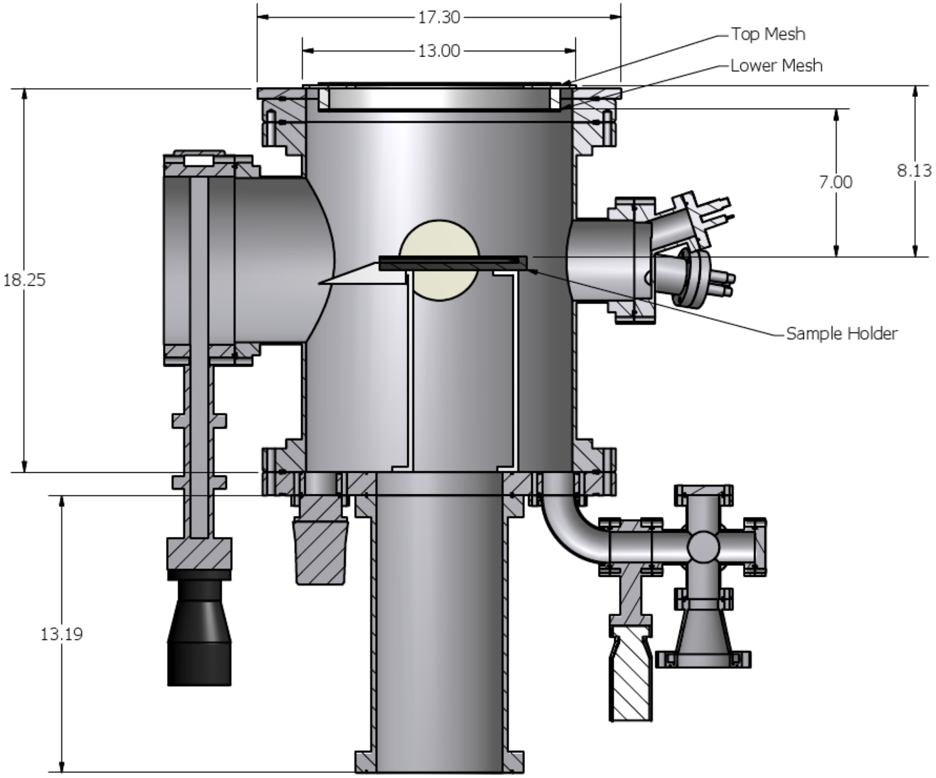
Electron Flux (alone)

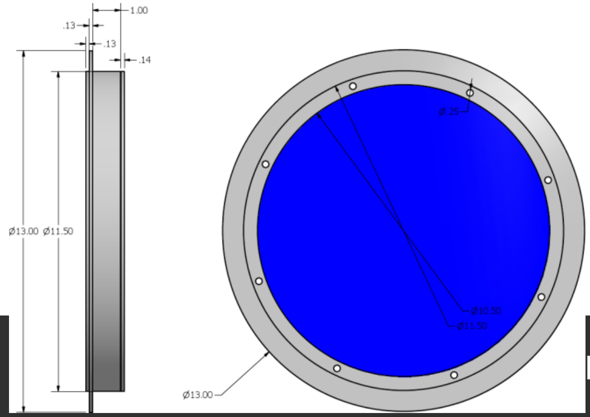
- Electrons in the plasma are in a distribution of energies
  - Even at large negative bias, some electrons make it to the surface
- Electric field brings in more electron flux
  - How do we know that it just isn’t electron flux?
  - The particles don’t fall apart in the scanning electron microscope
    - But what about in a 10 mTorr helium environment?

Electron Flux (alone)

- Block the plasma
  - Uses 3 fine mesh to block the plasma from reaching the sample
- Mesh is 4.67 % transparent
  - Very low metastable flux
  - High-energy electrons still make it to the sample

plasma source





Electron Flux (alone) does not cause removal

Bias to sample [V]	Current drawn [mA]
+5.2 ± 0.5	0.4 ± 0.1
+9.8 ± 0.5	0.8 ± 0.1

- 2 experiments
  - ☐ Negligible removal seen in each case however current drawn is similar to current drawn in high removal cases
- Earlier, removal was shown for a positive bias of +0 V, 0.54 mA (exposed to full plasma)
  - ☐ $5.9 \times 10^{6} \pm 2.7 \times 10^{5}$ nm^3/min
- Electron flux alone to the sample does not cause removal

Plasma conditions:
2 kW plasma, 10 mTorr He, 100 SCCM

Parameters Relevant to Removal

- Processing Time ✔
- Ion Flux ✔
- Electric Field ✔
- Electron Flux ✔ ✔
- Metastables
- Temperature

Parametric Approach:

(1) Systematically eliminate parameter to understand its effect

(2) Understand theory behind the physical parameter changed

(3) Use understanding from theory to predict the next removal experiment

Parameters Relevant to Removal

- Processing Time ✔
- Ion Flux ✔
- Electric Field ✔
- Electron Flux ✔ ✔
- Metastables ✔
- Temperature

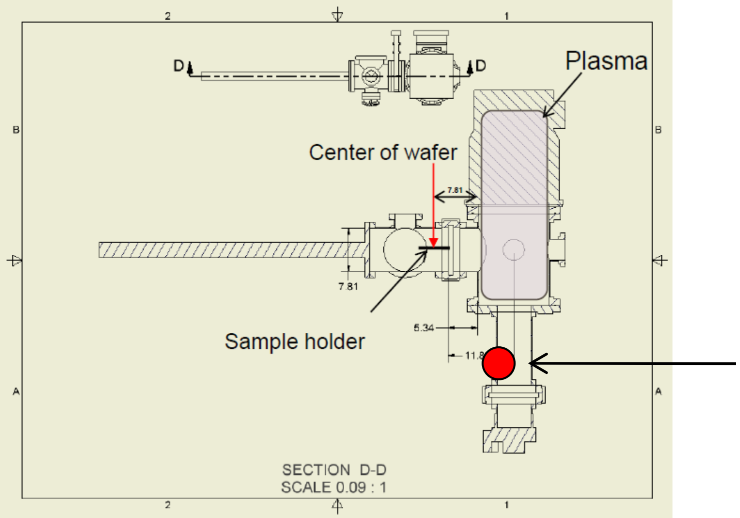
Parametric Approach:

(1) Systematically eliminate parameter to understand its effect

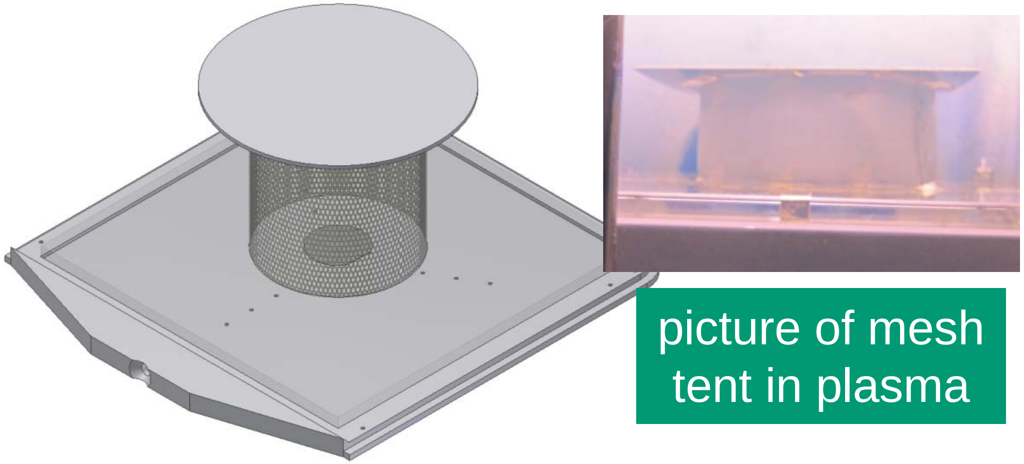
(2) Understand theory behind the physical parameter changed

(3) Use understanding from theory to predict the next removal experiment

Metastables Only?



(a) **Negligible removal observed**



picture of mesh tent in plasma

(b) **Negligible removal observed**

- Two tests designed to get only He metastables to the sample
  - No plasma or UV
- One held in load lock (a) above
- One surround by cylindrical mesh tent (b) above

Parameters Relevant to Removal

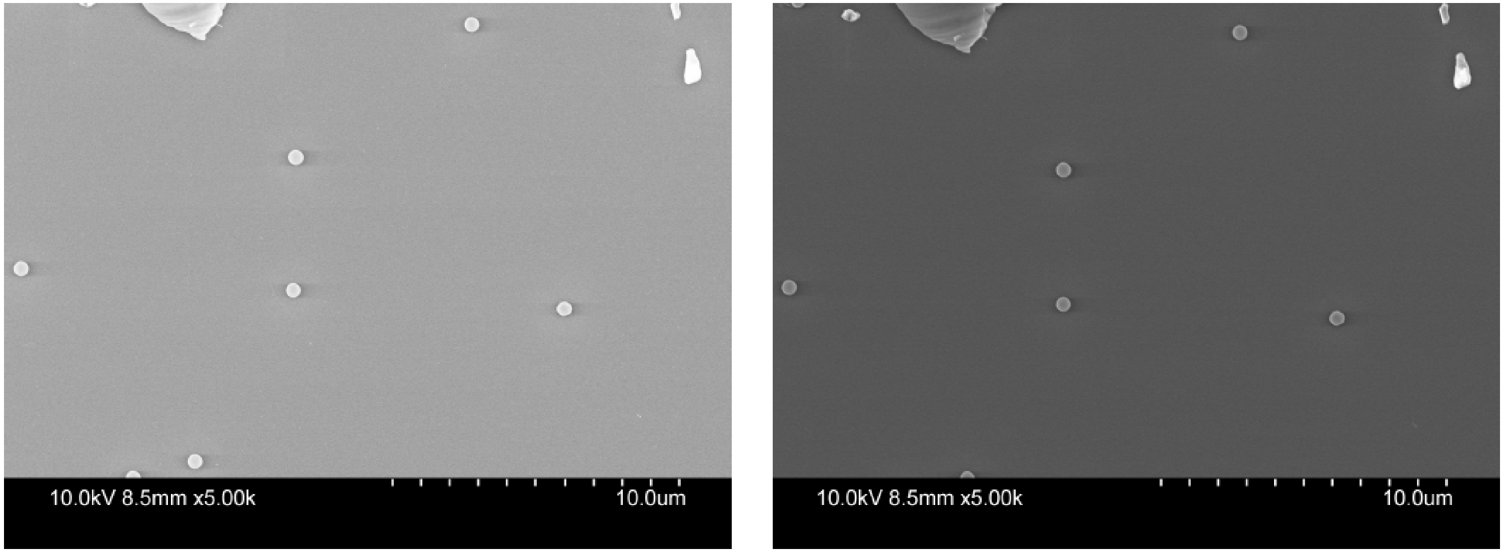
- Processing Time ✔
- Ion Flux ✔
- Electric Field ✔
- Electron Flux ✔ ✔
- Metastables ✔ ✔
- Temperature

Parametric Approach:

1. Systematically eliminate parameter to understand its effect
2. Understand theory behind the physical parameter changed
3. Use understanding from theory to predict the next removal experiment

Electric Field Only

- With the plasma-blocking mesh in place, an external electric field of 8.0x10^4 V/m was put on the sample



Before

After

Parameters Relevant to Removal

- Processing Time ✔
- Ion Flux ✔
- Electric Field ✔ ✔
- Electron Flux ✔ ✔
- Metastables ✔ ✔
- Temperature

Parametric Approach:

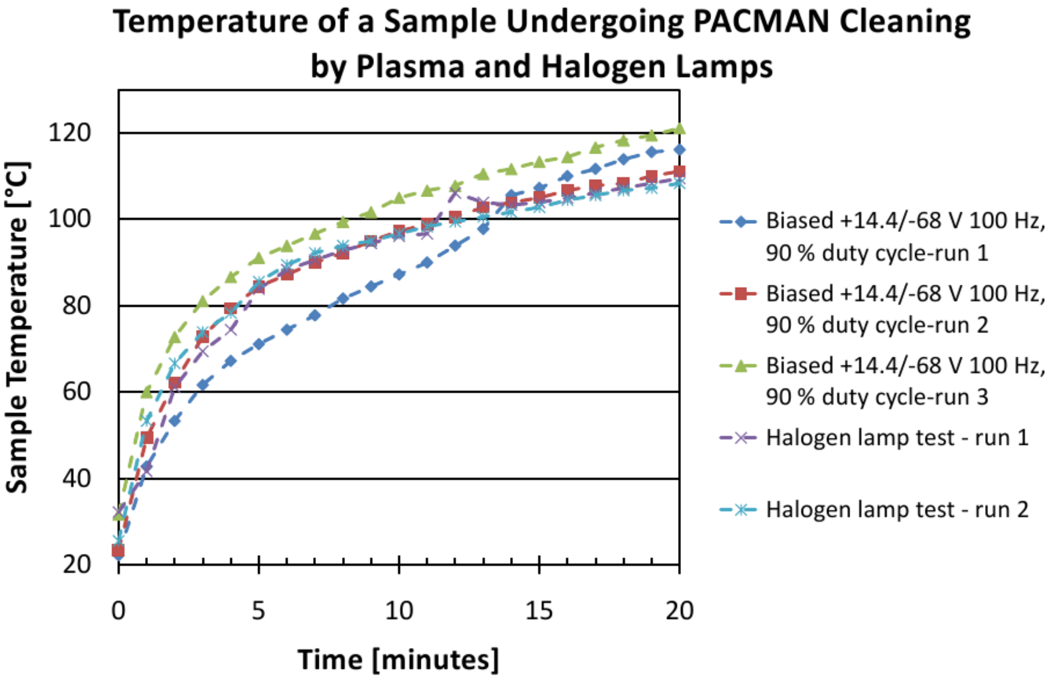
(1) Systematically eliminate parameter to understand its effect

(2) Understand theory behind the physical parameter changed

(3) Use understanding from theory to predict the next removal experiment

Heat Only

- Plasma heats the sample during PACMAN cleaning
  - Shown in the graph at right
  - Heating profile can be matched with halogen lamps
- Negligible removal (within measurement error) was observed for all heating tests.



A graph showing the temperature evolution of the wafer under plasma cleaning. Temp measurements ± 0.5 °C

Parameters Relevant to Removal

- Processing Time ✔
- Ion Flux ✔
- Electric Field ✔ ✔
- Electron Flux ✔ ✔
- Metastables ✔ ✔
- Temperature ✔

Parametric Approach:

(1) Systematically eliminate parameter to understand its effect

(2) Understand theory behind the physical parameter changed

(3) Use understanding from theory to predict the next removal experiment

What is needed for removal?

1. Electron flux,

Keeps broken bonds from reforming

2. Electric field (pointing from the surface into the plasma is best),

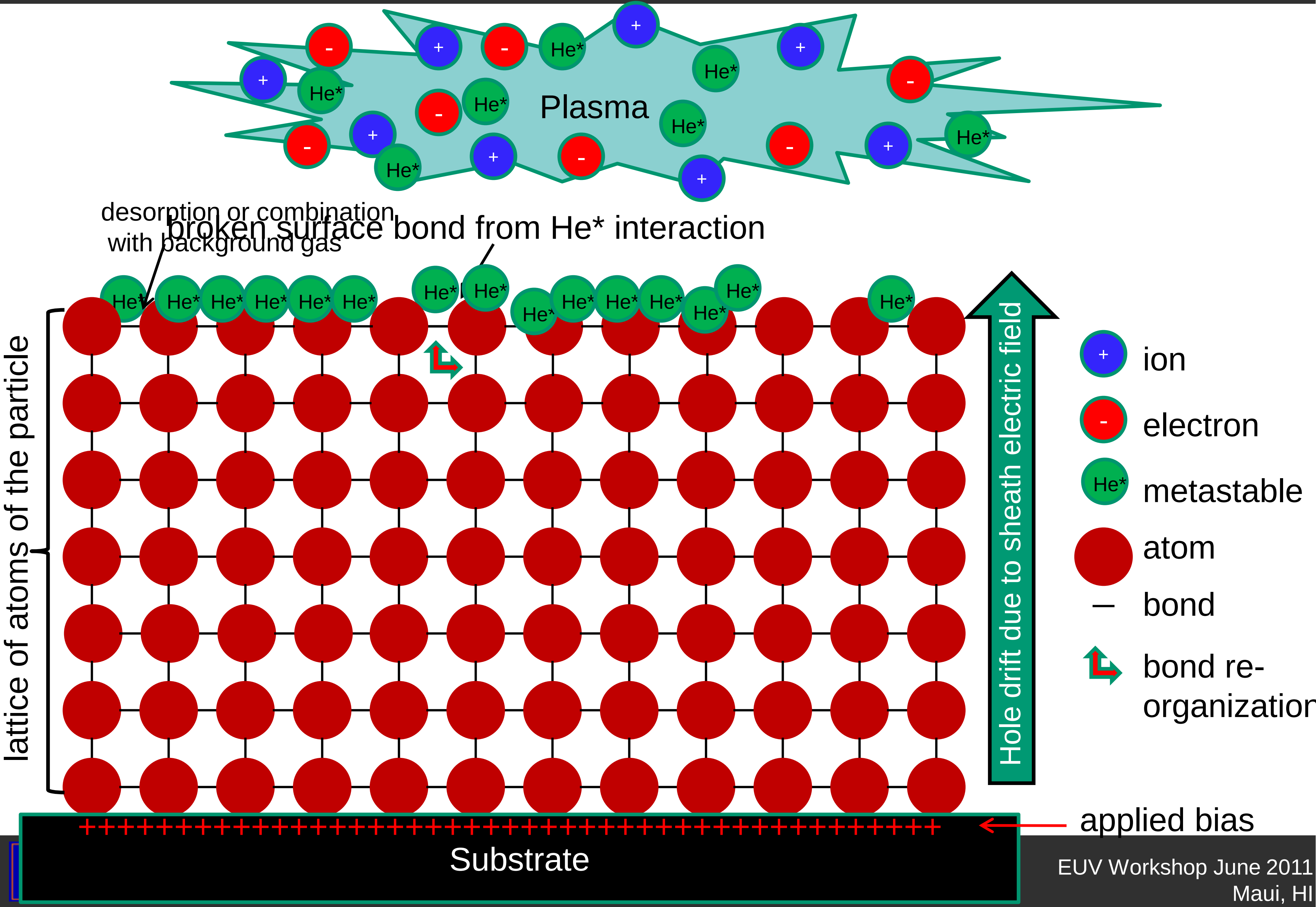
Keeps “holes” near surface where they can be used

3. And in presence of metastables

Breaks the bonds

The rate-limiting effect is maintaining broken bonds to allow for volatilization

Removal Mechanism



Plasma

desorption or combination
with background gas

broken surface bond from He* interaction

lattice of atoms of the particle

Hole drift due to sheath electric field

ion

electron

metastable

atom

bond

bond re-
organization

applied bias

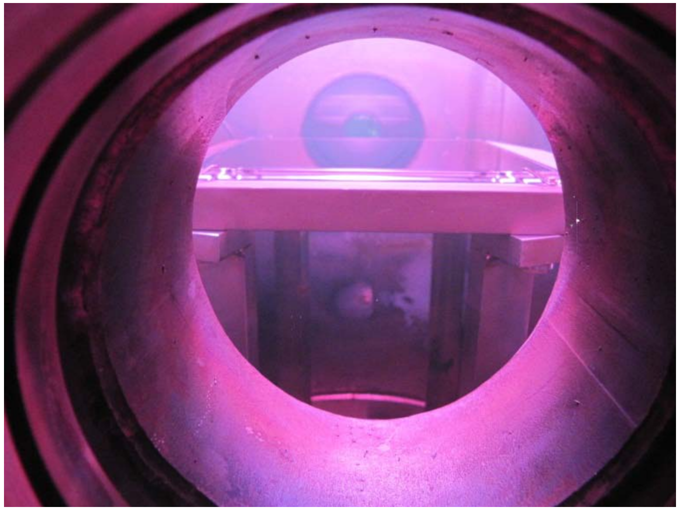
Substrate

Important Parameters: Need all 3

- Maximize electric field pointing from surface to plasma ✓
- Maximize electron flux to the sample ✓
- Maximize helium metastable density ✓
- Removal in this fashion yields the maximum removal rate!

$1.2\text{x}10^{7} \pm 5.1\text{x}10^{5}\ \text{nm}^{3}/\text{min}$

Picture of cleaning full-sized EUV mask blank in PACE



Conclusions/Summary

- The PACMAN cleaning techniques works on carbon and hydrocarbons and is now understood
- Currently operating with a pulsed bias (less disruption of a plasma than positive bias) to clean carbon/hydrocarbon contaminants from EUV mask blanks has been done and is being incorporated into some cleaning systems
- Thoughts of adding “gas-cocktail”
  - N, H, O added to He plasma to aide in the removal of inorganic contaminants