Extending CO_2 Cryogenic Aerosol Cleaning for EUV Mask Cleaning (P57)

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06/16/2016

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Outline

- Motivation / Cleaning Challenges
- CO_2 Cleaning in Production for Advanced Node Optical Masks
- EUV mask FS cleaning results
- EUV mask BS cleaning results
- Remarks and Conclusions

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Motivation / Cleaning Challenges

- Removal of all soft defects (particles)
  - Adhesion forces dominate volume and area proportional forces, hence smaller particles are more difficult to remove
  - BS e-chucked defect removal
  - FS native particle removal
- Zero damage to features on FS (w/o pellicle)
  - Smaller features
  - Higher Aspect Ratio features
- No reduction to mask lifetime due to cleaning
  - Transmission/Reflectivity loss, Phase loss or CD change
  - Haze/progressive defects, ESD
  - No adders

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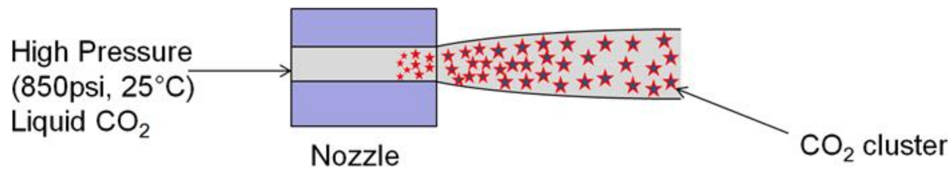
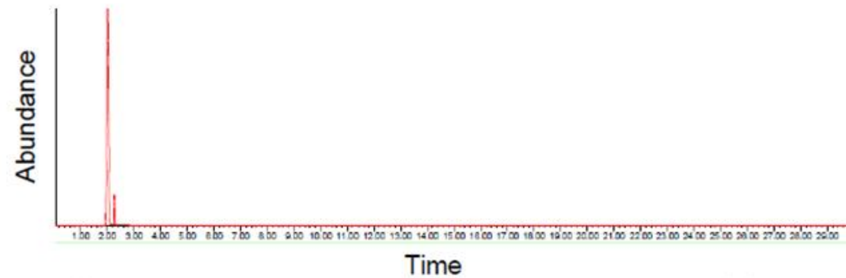
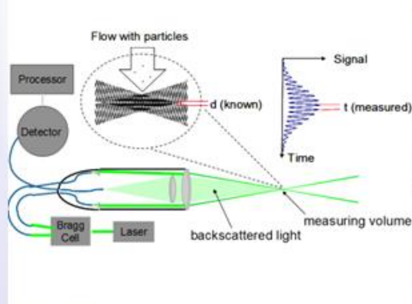
Overview of CO_2 Cleaning

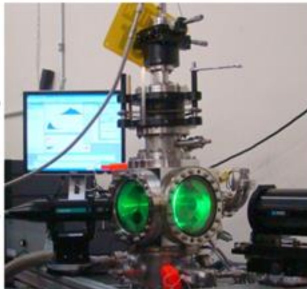


Formation of CO2 cluster with sufficient momentum for cleaning

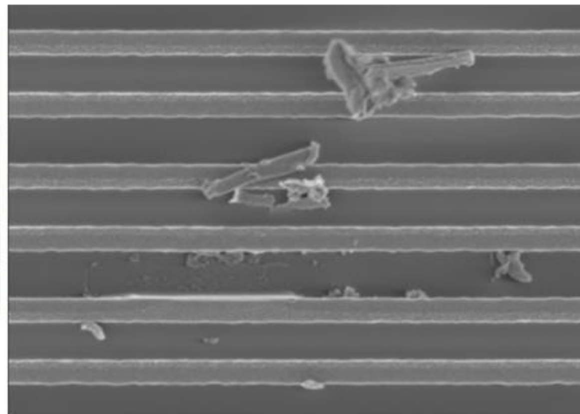


Ultra-high purity CO_2

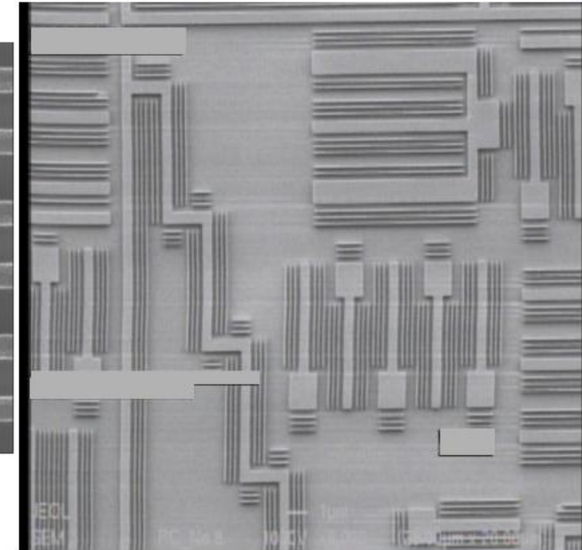




Phase Doppler Anemometry for CO2 Spray Characterization



Repair debris removal



Damage free Cleaning

Optimum Momentum of Ultra-pure CO_2 clusters Cleans Particles and Repair Debris without damage

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Overview of CO_2 Cleaning

Why CO_2 aerosol cleaning technique?

- Dry, Chemistry-free process: No mask degradation
  - No haze
  - No loss in transmission/reflectivity, No Phase or CD change
- Unlimited number of cleans: Mask Lifetime extended
  - Compliment traditional cleans
  - Enable new cleans
- Damage-free cleans:
  - No pits
  - No small feature damage
  - No ESD

CO_2 Cleaning has delivered production solutions

EL-C™ Mask Cleaning Applications

- Wafer fab - Mask backside cleaning (with pellicle on)
- Backside Cleaning (mask shop)
- EUV-backside E-chucked defects

- Pre repair clean (differentiates "soft" verses "hard" defects that require repair)
- Post repair (RAVE Merlin™) debris cleaning
- Final Clean Capability (pre-pellicle for replacing wet)
- Cleaning of process adders from other tools
- Blank Mask Cleaning
- Front Side Cleaning (next to pellicle)

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Optical Mask Cleaning Data (Production)

For Wafer Fab
OHT Capable

For Mask Shop

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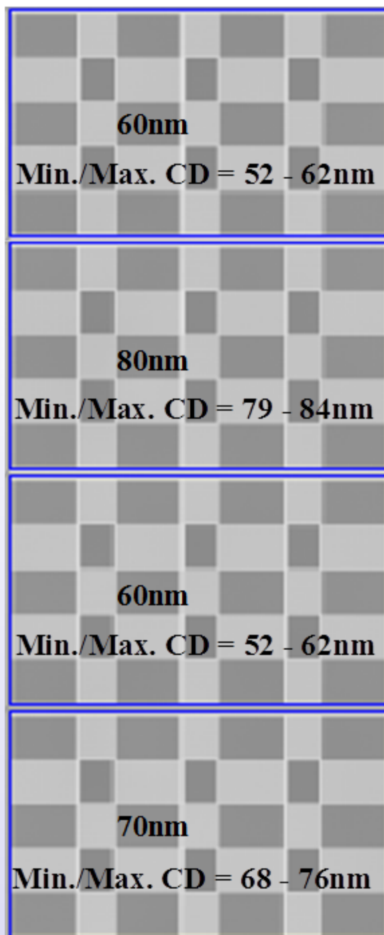
Damage-free Cleaning Capability

High Aspect Ratios (up to 2.8)



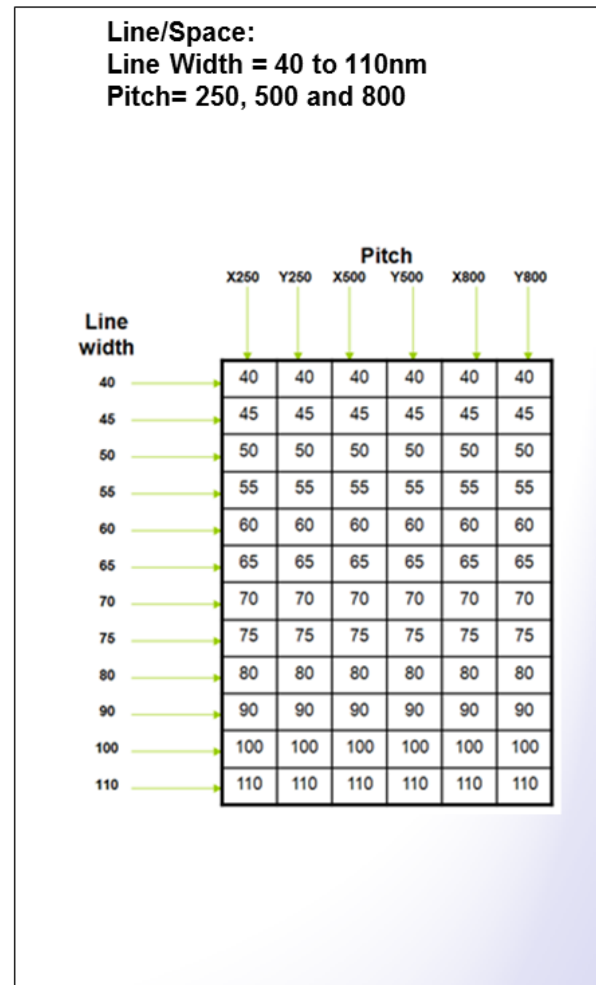
Aspect Ratios (up to 1.5)

60nm 60nm 60nm 60nm
Min./Max. CD = 55 - 66.5 nm
70nm 70nm 70nm 70nm
Min./Max. CD = 65 - 75 nm
80nm 80nm 80nm 80nm
Min./Max. CD = 75 – 85.5 nm

Dark Assist Features (DAFs) with a stack height of 82 nm

SRAF Damage afo Nozzle Height and SRAF Width		Nozzle Height (a.u.)					Data from 2013
		16	14	13	11	10	
Average SRAF Width (in nm)	34	1	0	3	5	6	Total No. of Broken SRAFs on entire mask, after a 2x Full Mask CO2 Cleaning
	36	0	0	1	1	1	
	37	0	0	0	0	0	
	40	0	0	0	0	0	
	42	0	0	0	0	0	

Aspect Ratios (up to 1.75)



Line width	X250	Y250	X500	Y500	X800	Y800
40	40	40	40	40	40	40
45	45	45	45	45	45	45
50	50	50	50	50	50	50
55	55	55	55	55	55	55
60	60	60	60	60	60	60
65	65	65	65	65	65	65
70	70	70	70	70	70	70
75	75	75	75	75	75	75
80	80	80	80	80	80	80
90	90	90	90	90	90	90
100	100	100	100	100	100	100
110	110	110	110	110	110	110

Damage-free CO_2 Cleaning of SRAFs as small as 37 nm demonstrated on full mask on Optical Mask

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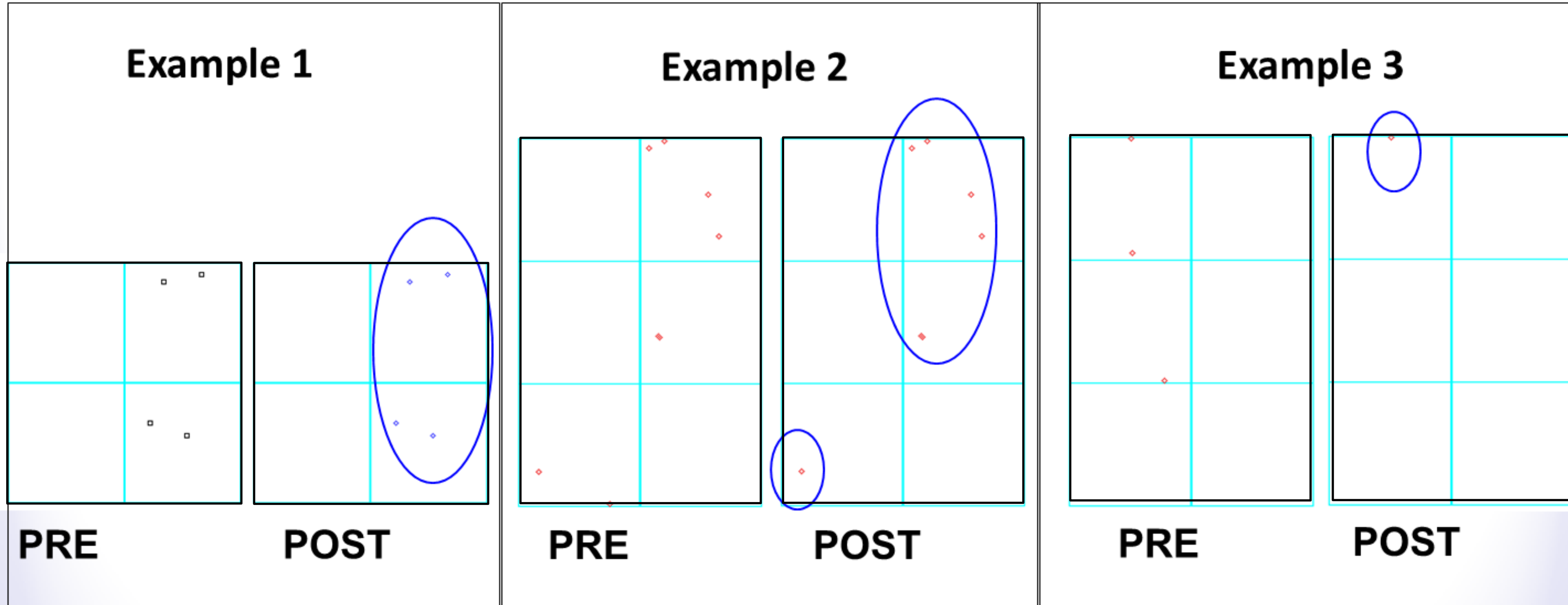
Pre-Repair Clean Capability

(differentiates "soft" verses "hard" defects that require repair)



- Results showing removal of isolated soft defects on optical masks
- Zero adders and no pattern damage with CO_2
- All remnant particles were hard defects and successfully nanomachined

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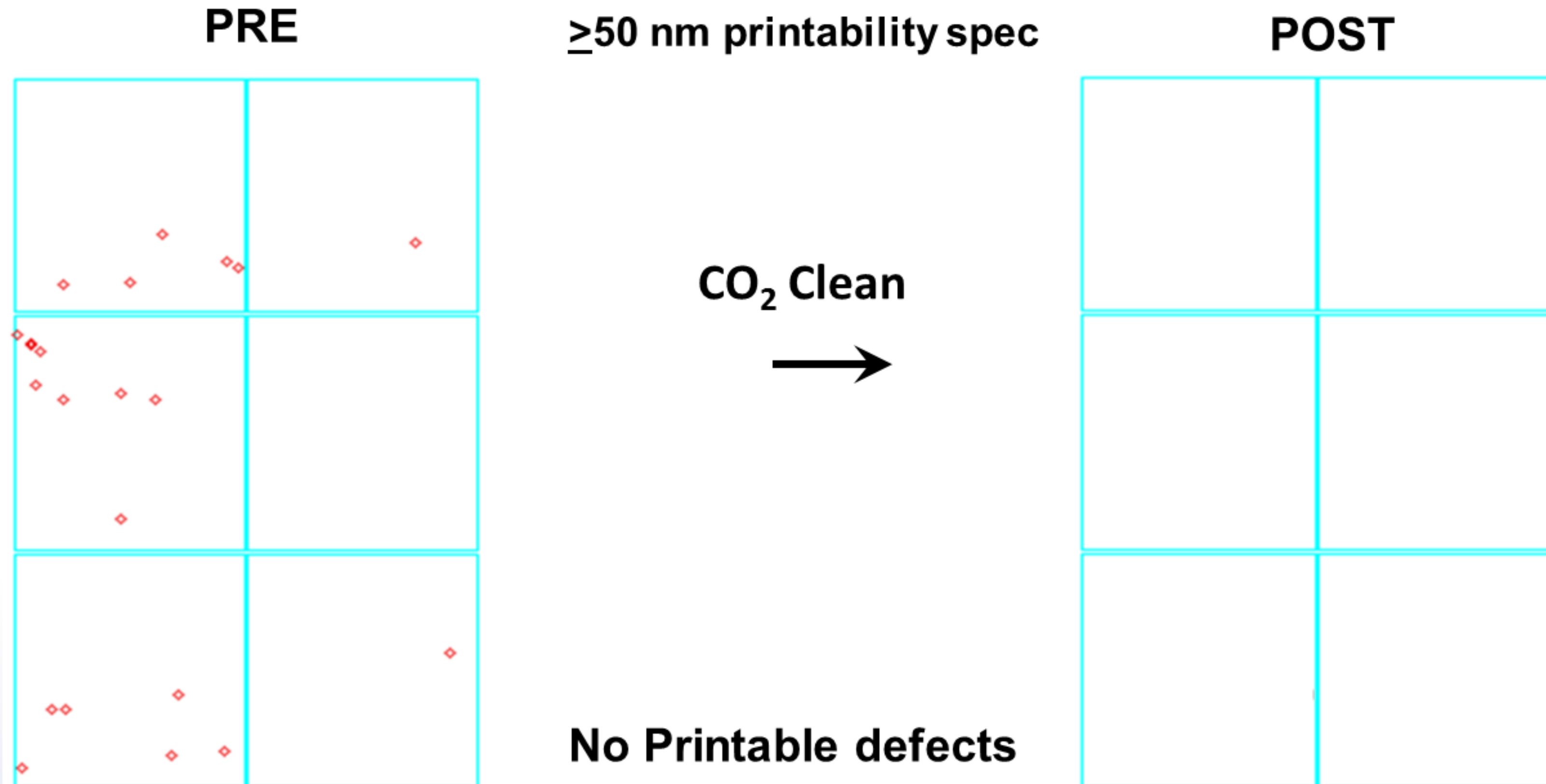
Final Clean Capability

(pre-pellicle for replacing wet)



100% removal of all 21 particles including 7 large (>1µm) defects.
No pattern damage observed on optical mask.

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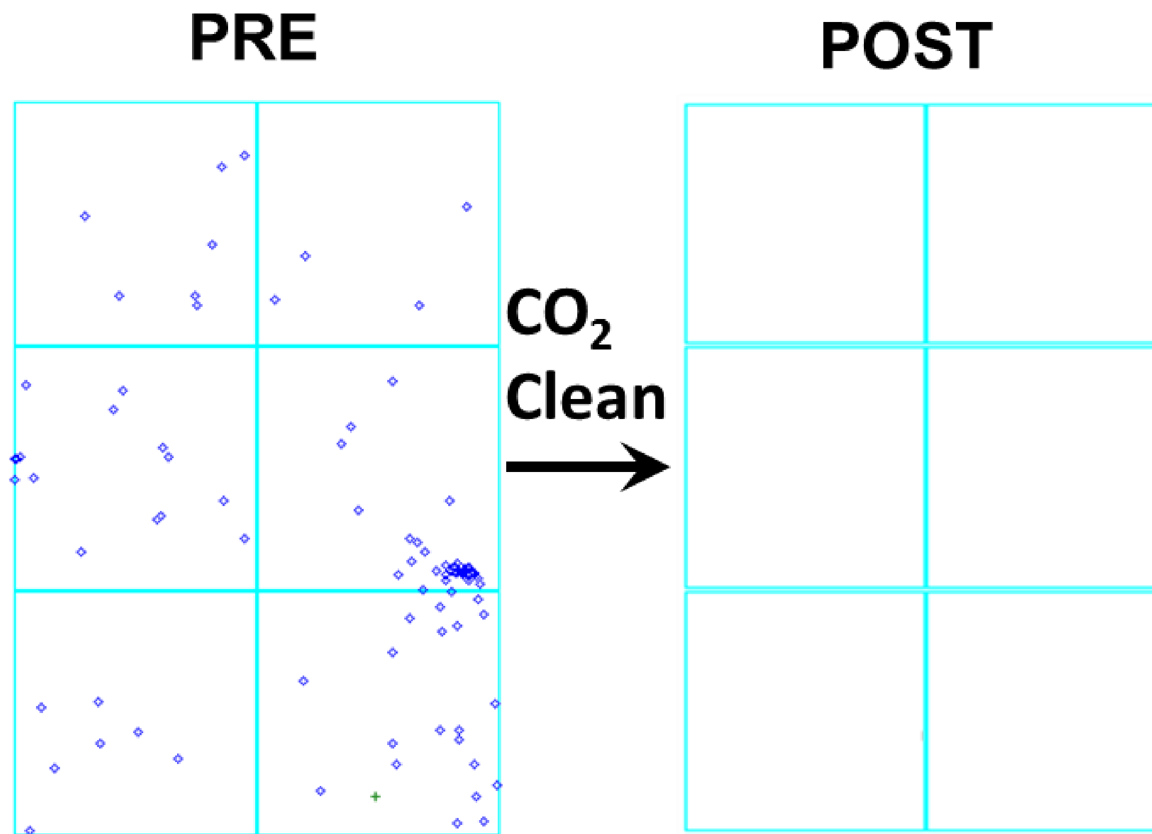
Cleaning Capability of Process Adders from Other Tools on Optical Masks



≥50 nm printability spec

100% removal of all contamination including 40+ Large particles (>1µm).
No pattern damage was observed.

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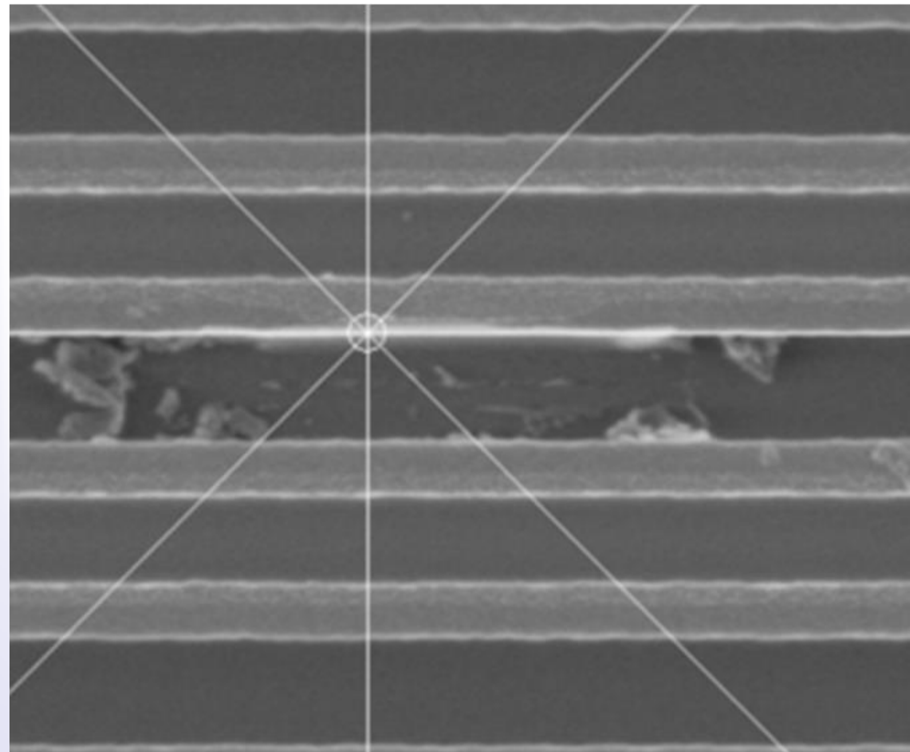
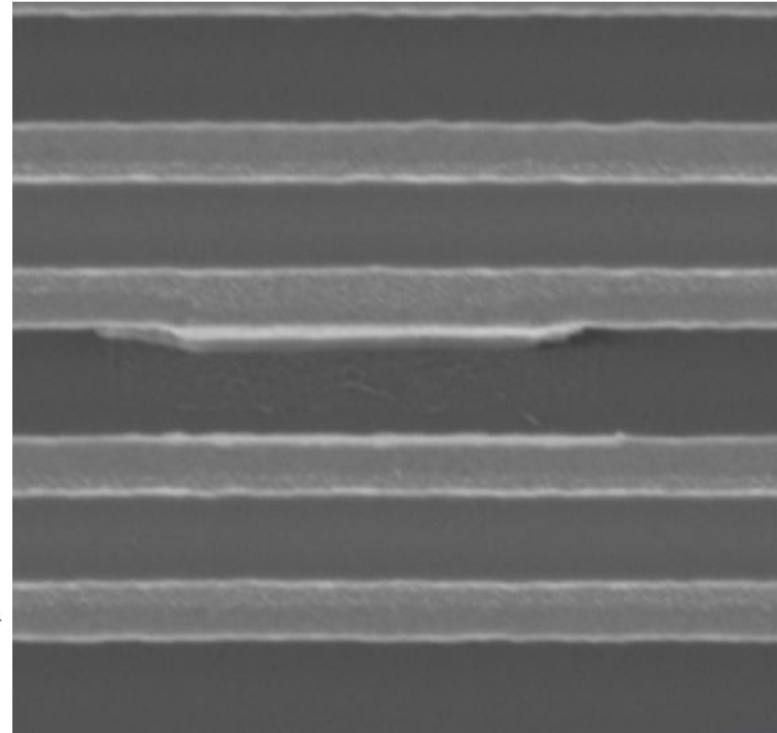
Post Repair debris Cleaning

Sub-30nm Defect Removal Capability



CO_2 Clean



Post nanomachining repair debris (quartz, MoSi) on advanced node mask

100% Removal of all Printable Debris

100% removal of all printable Post nanomachining repair debris.

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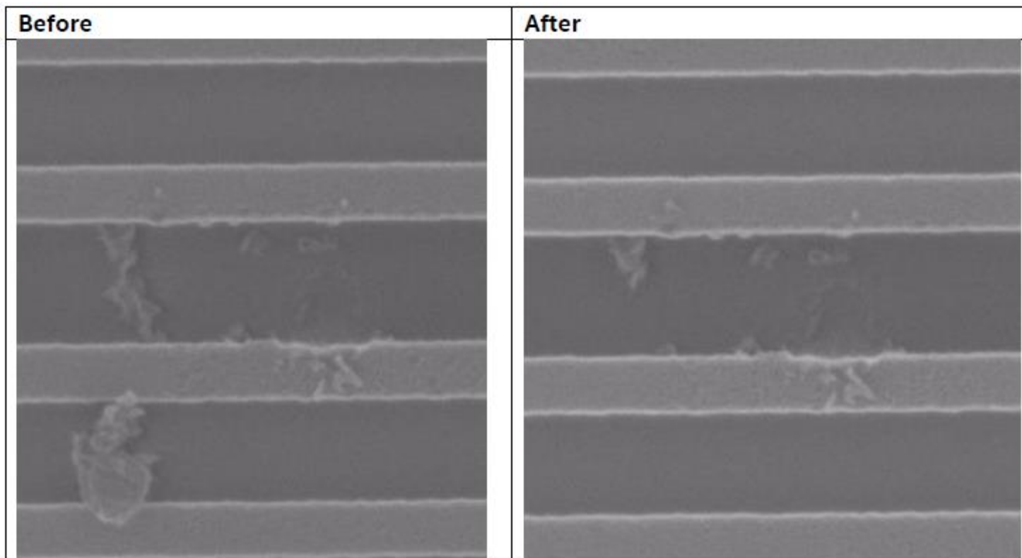
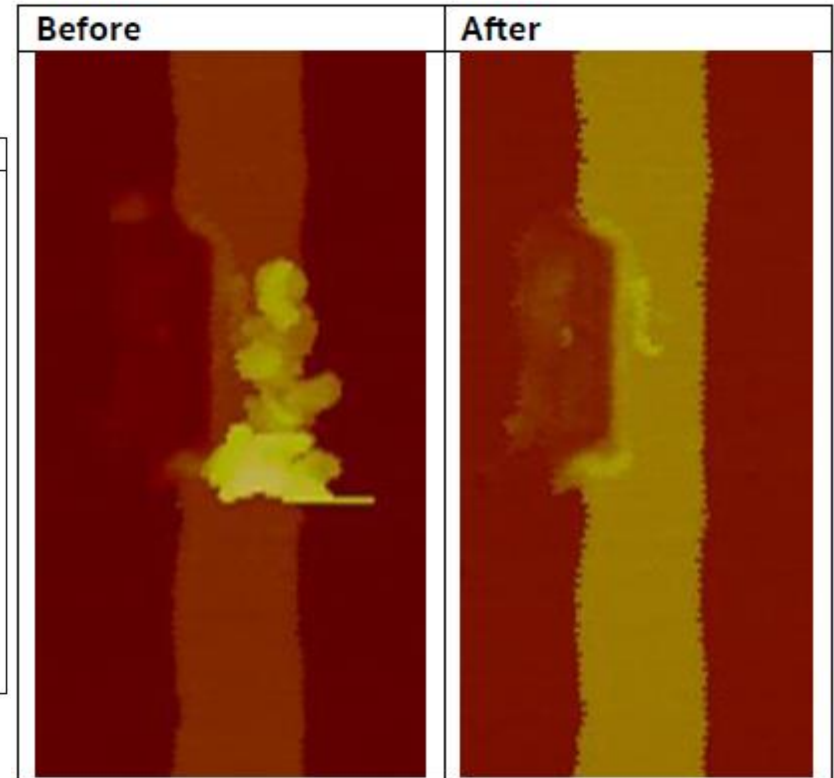
Post Repair debris Cleaning

Sub-30nm Defect Removal Capability





SEM Images Mask #1

AFM Images Mask #2

Satisfactory AIMS printability results on Pilot advanced masks Post CO_2 clean.

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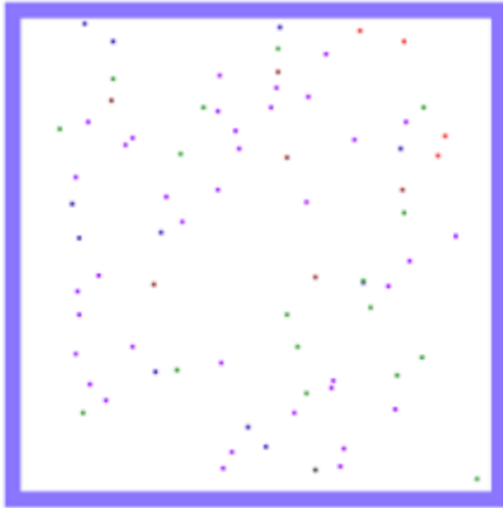
EL-C^{TM} EUV Mask Cleaning

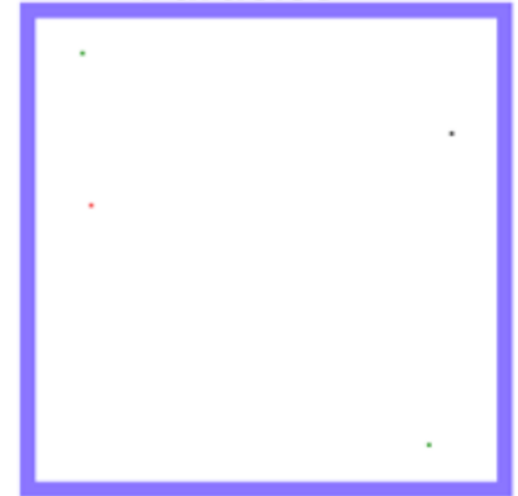
- EUV Front Side Cleaning
  - Native Particles
  - Ru Film Damage-free Cleaning
- EUV Back Side Cleaning
  - Native Particles
  - E-chucked Defects

EUV Front Side CO_2 Cleaning Capability

Removed Particles

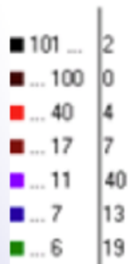


New and/or Re-deposited Particles



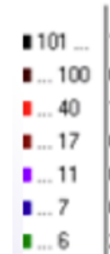
Pixel 6 corresponds to 50 nm particle. Inspection below pixel 6 ignored because of less than 100% Capture Rate

Pixel Histogram



79 defects at pixel 6+

Pixel Histogram



4 defects at pixel 6+

CO_2 cleaning capable of removing 50nm inorganic particles on EUV mask blanks similar to optical masks.

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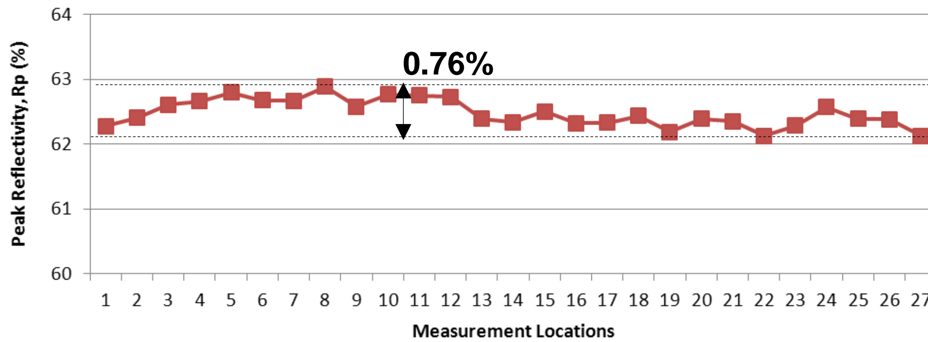
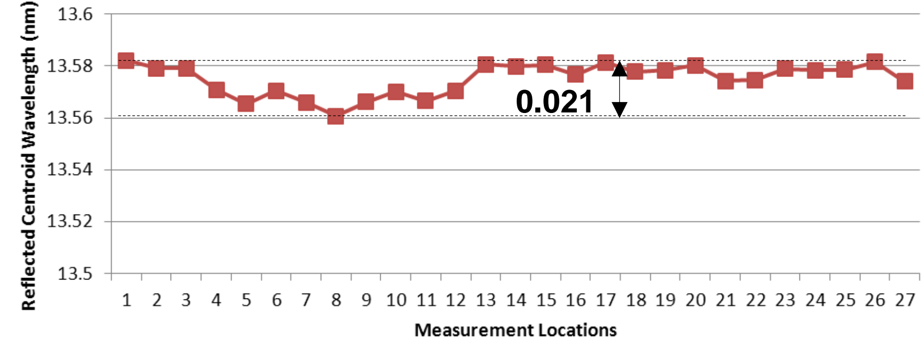
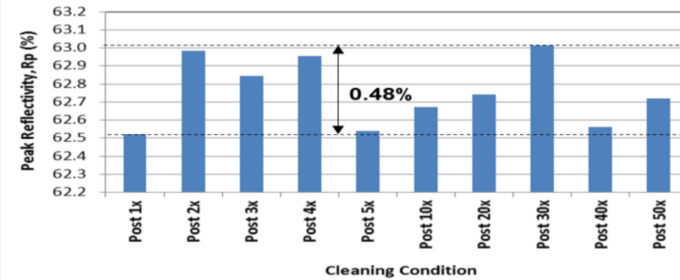
EUV Front Side Cleaning (50x Cleans Ru)

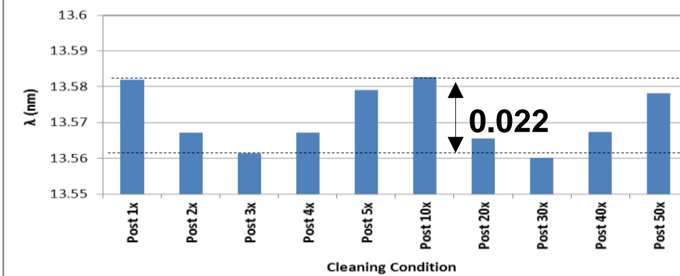
EUV Reflectometer Measurements







EUV Blank: CrN, LTEM, 50 ML Mo/Si, 2.5nm Ru



EUV Reflectometer Measurements

Mask EUV Reflectivity (ML Stack+Ru)	Pre CO2 (27 Points)		Post CO2: 1x,2x,3x,4x,5x (5 Points)		Post CO2: 10x,20x,30x,40x,50x (5 Points)	
	Peak Reflectivity Rp (%)	Centroid λ (nm)	Peak Reflectivity Rp (%)	Centroid λ (nm)	Peak Reflectivity Rp (%)	Centroid λ (nm)
Average	62.48	13.575	62.77	13.571	62.74	13.571
Maximum - Minimum	0.76	0.021	0.46	0.022	0.45	0.022

No degradation of the Ru film after 50x CO_2 Cleans. Post 1x to Post 50x clean no change in Reflectivity in EUV light.

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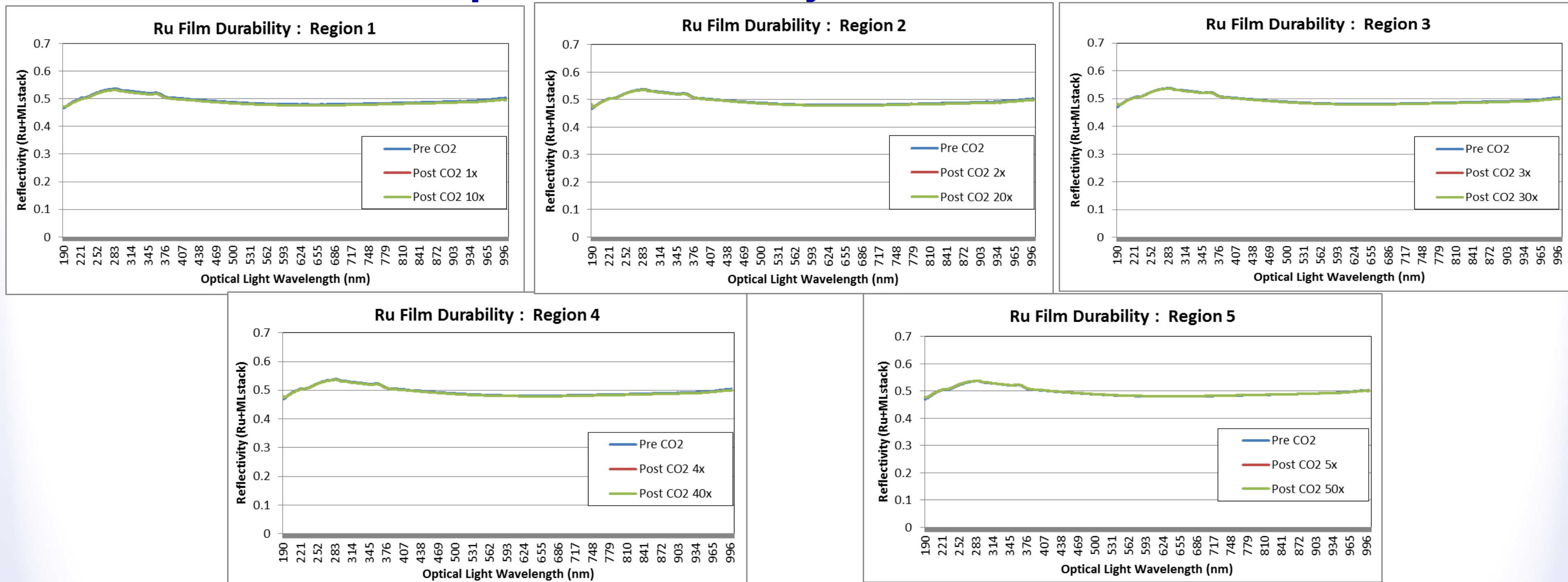
EUV Front Side Cleaning (50x Cleans Ru)

Optical Reflectivity Measurements



Optical Reflectivity Measurements

% Reflectivity (ML+Ru) @257 nm	Region 1			Region 2			Region 3			Region 4			Region 5		
	Pre	1x	10x	Pre	2x	20x	Pre	3x	30x	Pre	4x	40x	Pre	5x	50x
	52.55	52.23	52.23	52.62	52.56	52.56	52.63	52.61	52.61	52.62	52.56	52.56	52.53	52.76	52.76

Average Reflectivity (ML+Ru) @ 257 nm	Pre CO2	Post CO2 (1 - 5 x)	Post CO2 (10 - 50 x)
	52.59	52.54	52.54

No degradation of the Ru film after 50x CO_2 Cleans. Post 1x to Post 50x clean no change in Reflectivity in Optical light.

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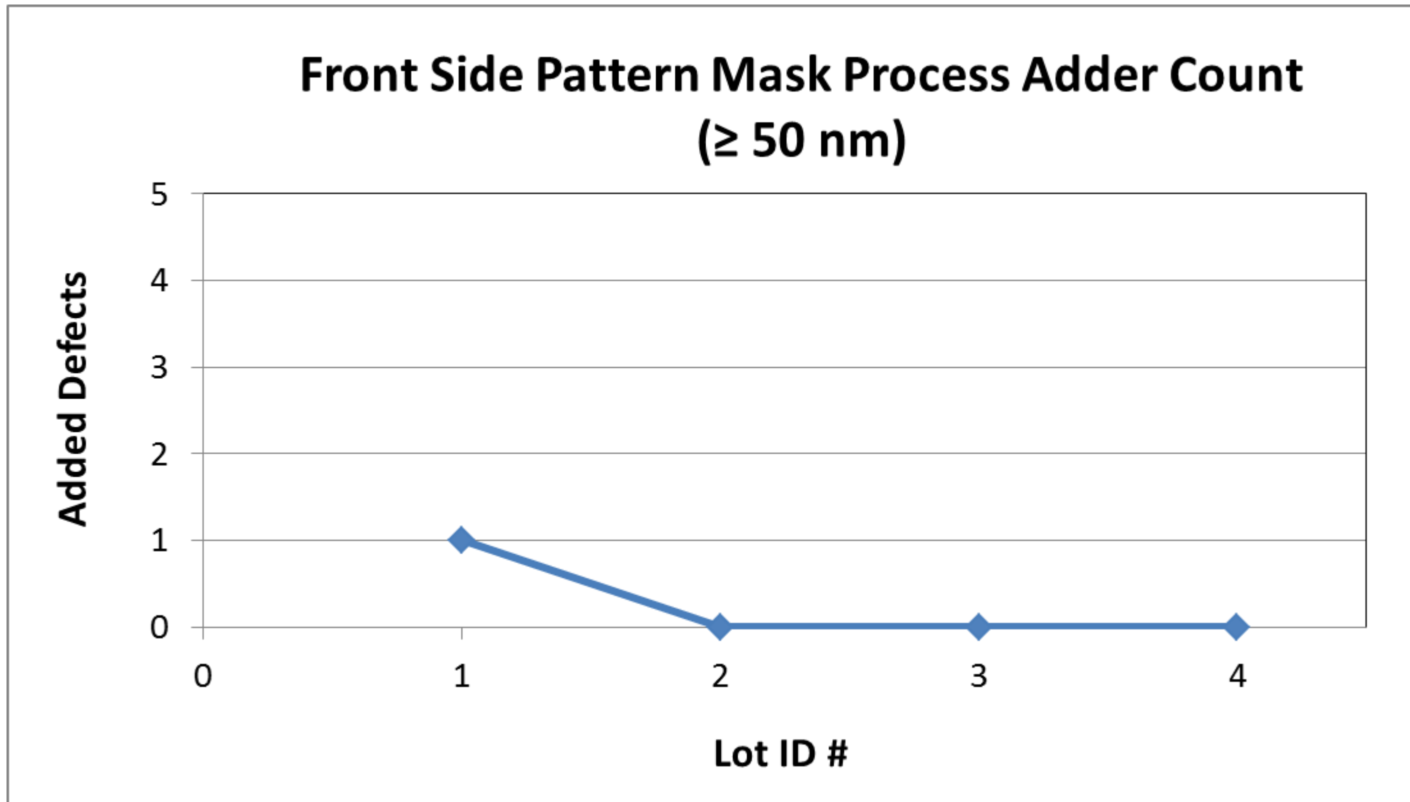
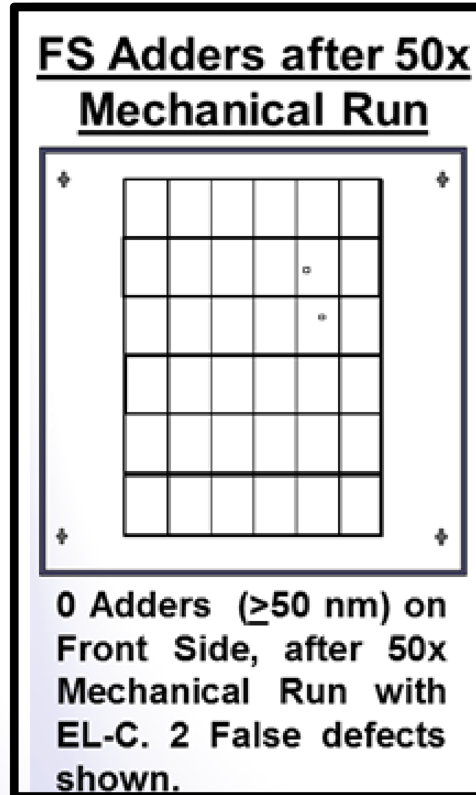
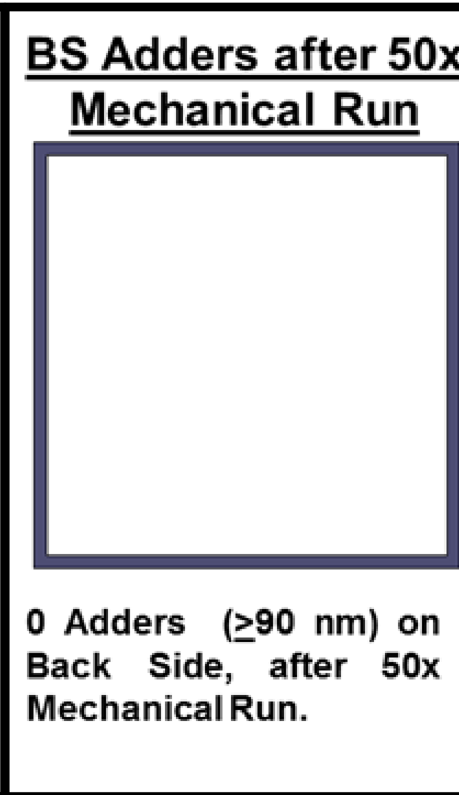
EUV Front Side Process Cleanliness

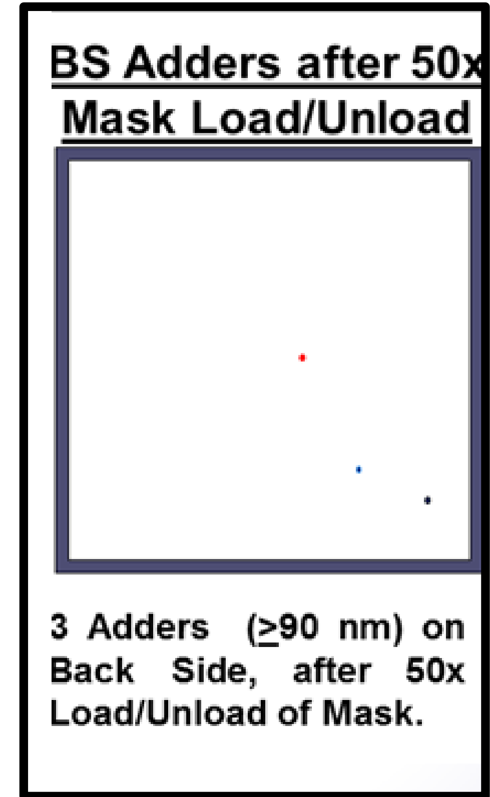


Demonstrated Zero Front Side Process Adders (≥ 50nm) on 3 back to back runs of CO_2 cleaning

EL-C System Environment and Handling Mechanisms Cleanliness







EL-C demonstrated Clean Handling Mechanisms and Environment (No CO_2)

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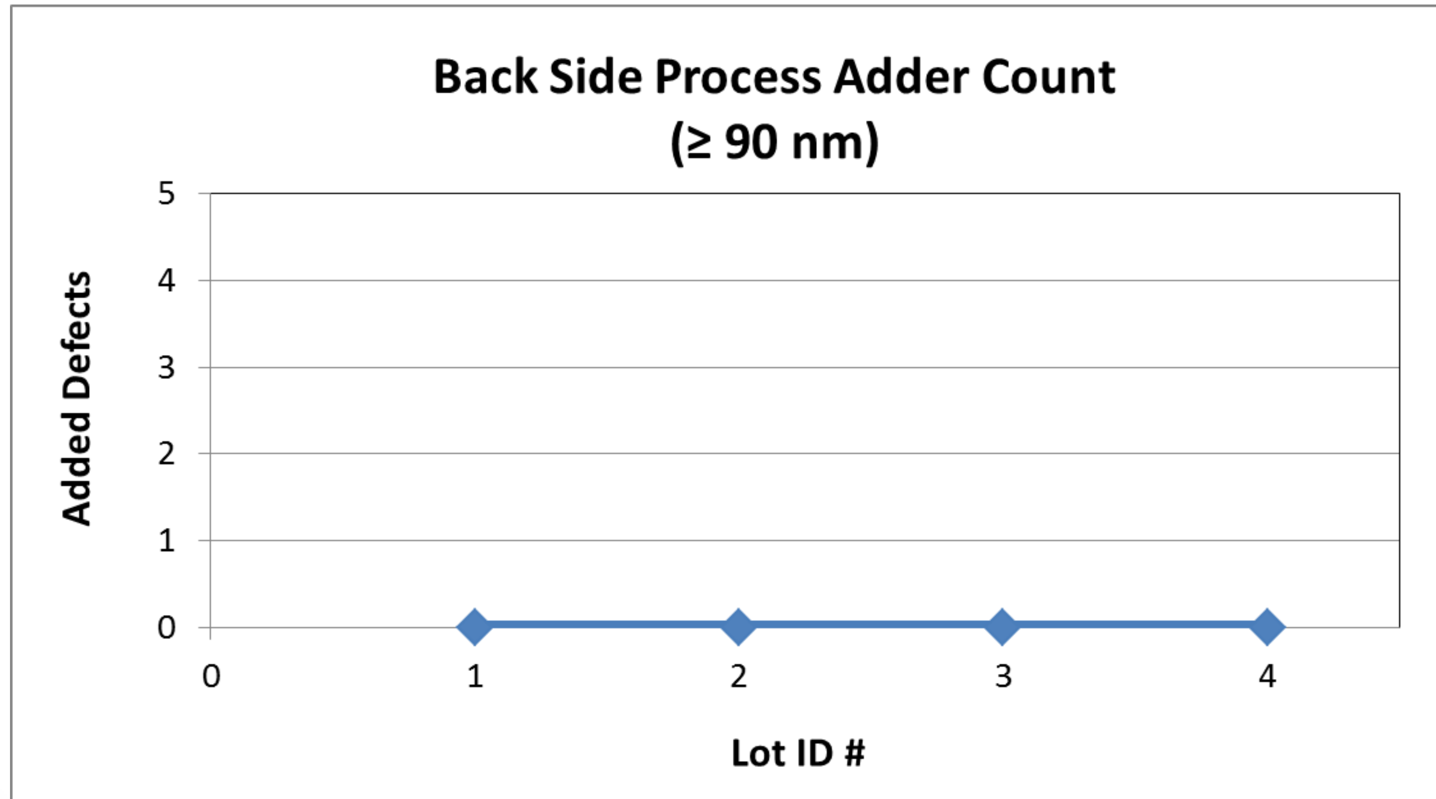
EUV Back Side Process Cleanliness



Demonstrated Zero Process Adders on 4 back to back CO_2 cleans

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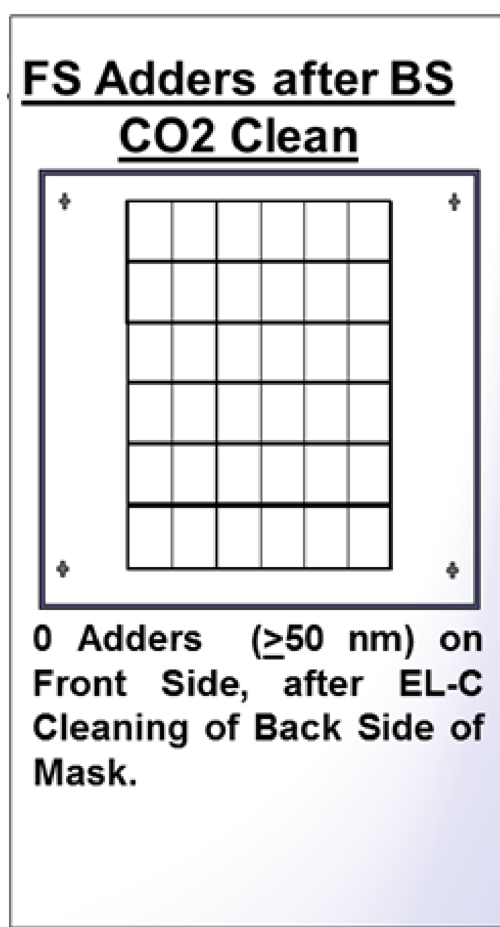
EUV Back Side Cleaning without Front Side Cross- Contamination



Demonstrated Zero Front Side Adders (≥ 50nm) after Backside CO_2 Cleaning

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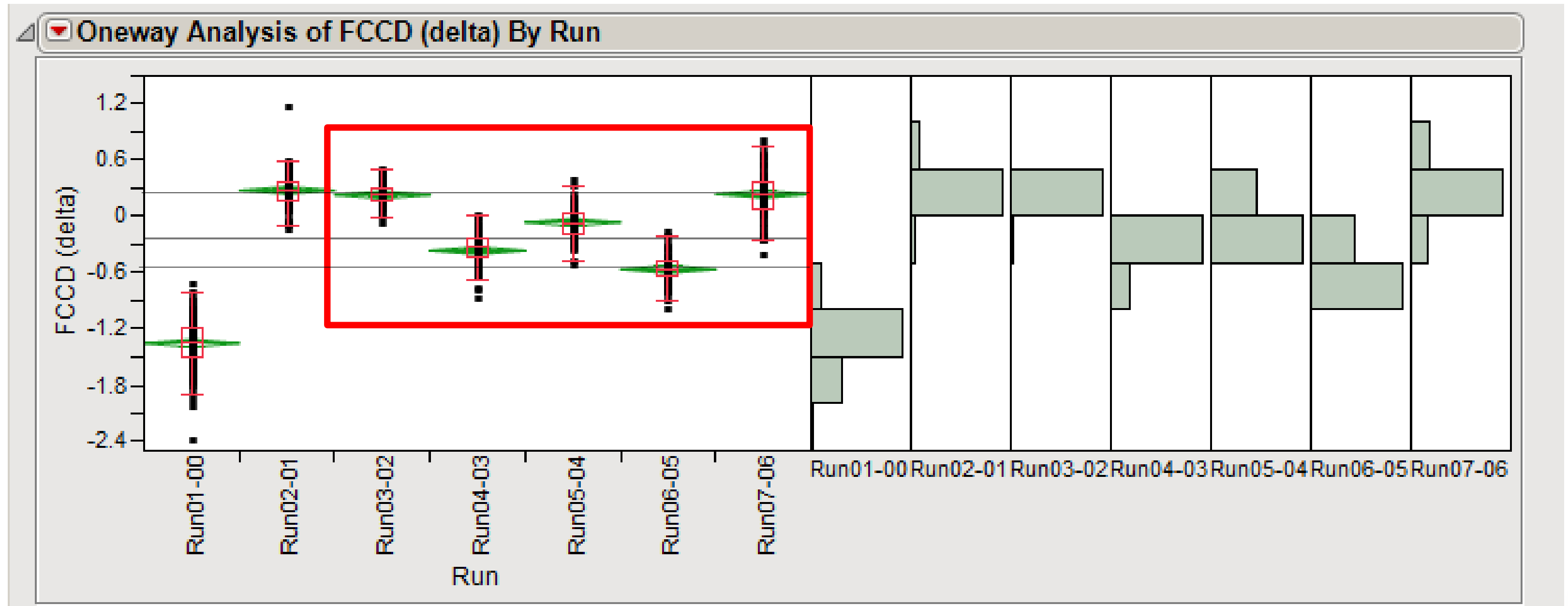
EUV Pattern Mask FCCD (delta) uniformity analysis



No visible CD [Final Check CD(delta)] changes (< 1 nm) on pattern mask after 5x Back side CO_2 cleans

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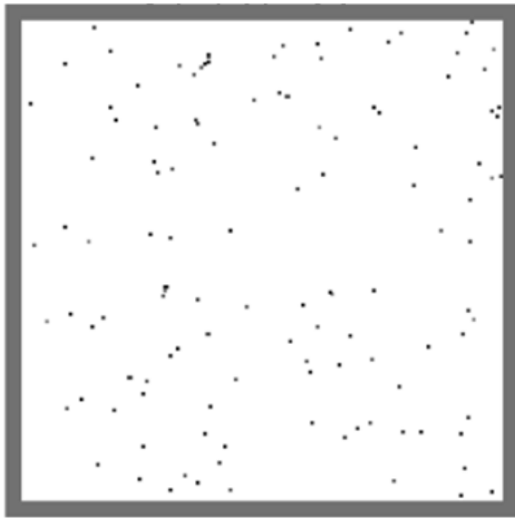
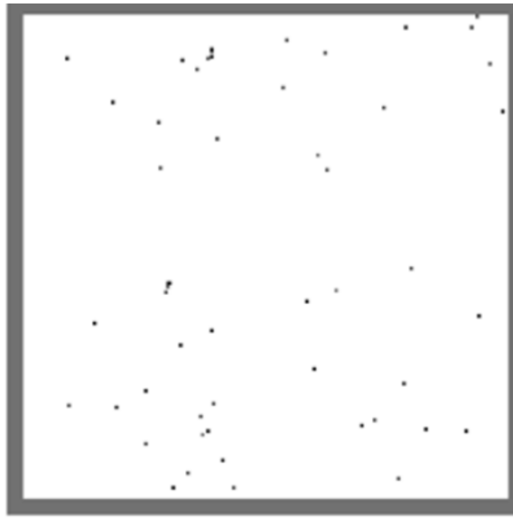
EUV Back Side Cleaning Capability
(Native Particles ≥ 1µm)

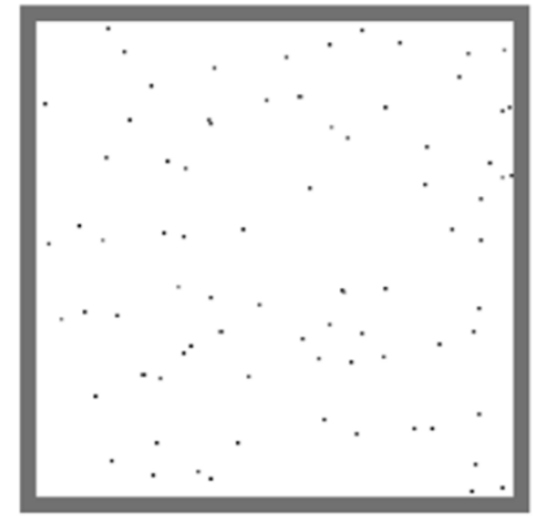
Pre Clean



Post Clean



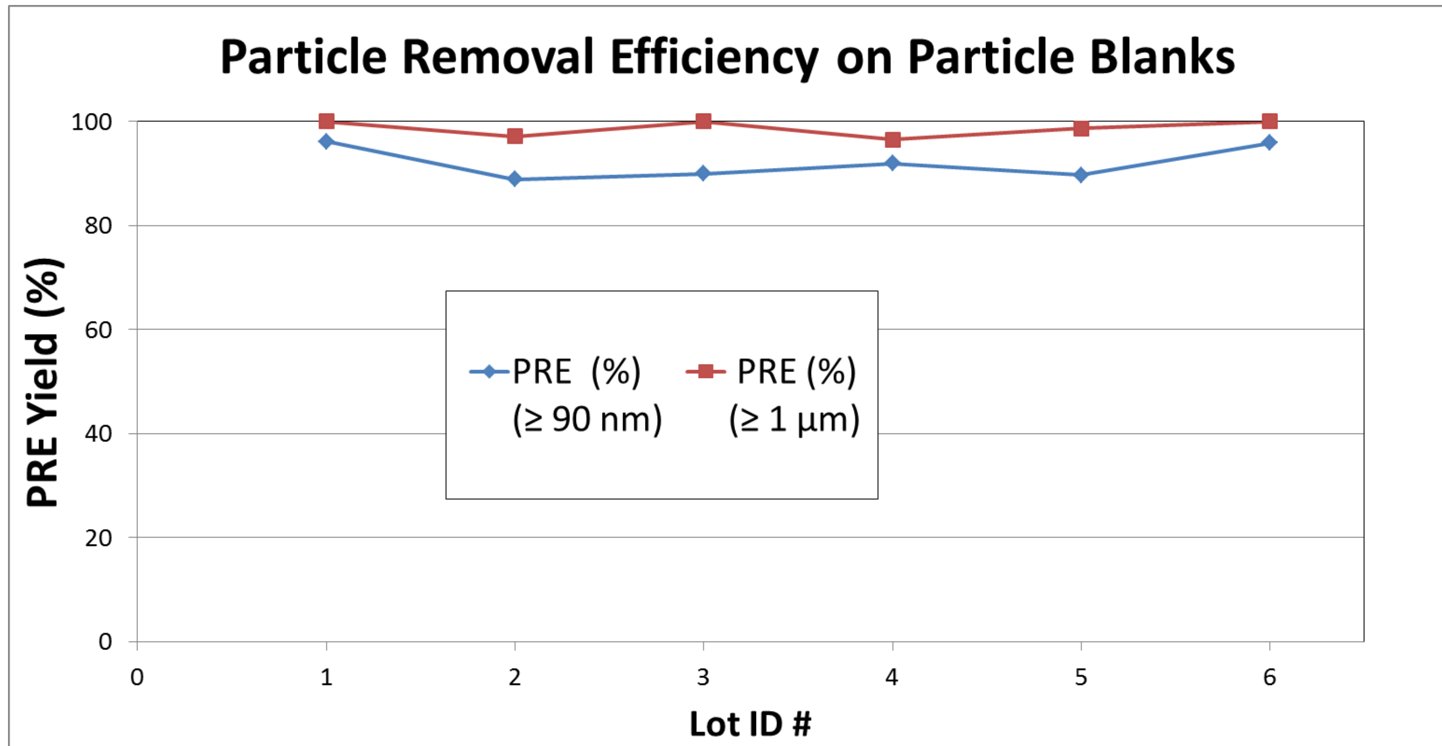
Particles Removed



Demonstrated 100% removal of native particles (≥ 1µm) on Back Side of EUV Mask Blank with CO_2 Cleaning

EUV Back Side Cleaning Capability

Native Particles



Back Side CO_2 Cleaning PRE performance on native particles on EUV blank masks:

- **PRE 90% @ ≥ 90 nm**
- **PRE 99% @ ≥ 1 µm**

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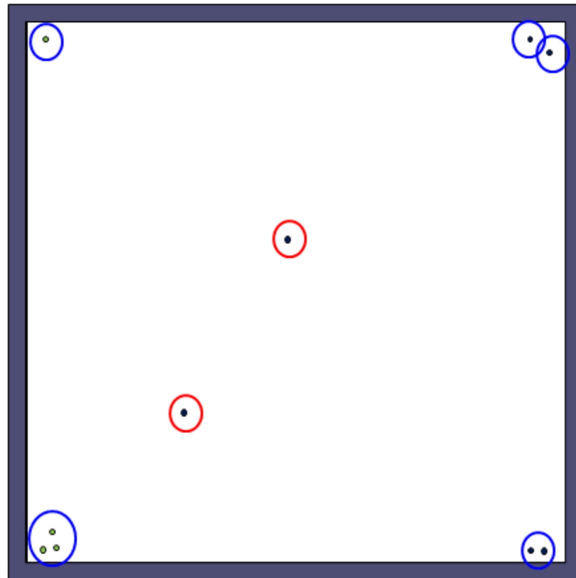
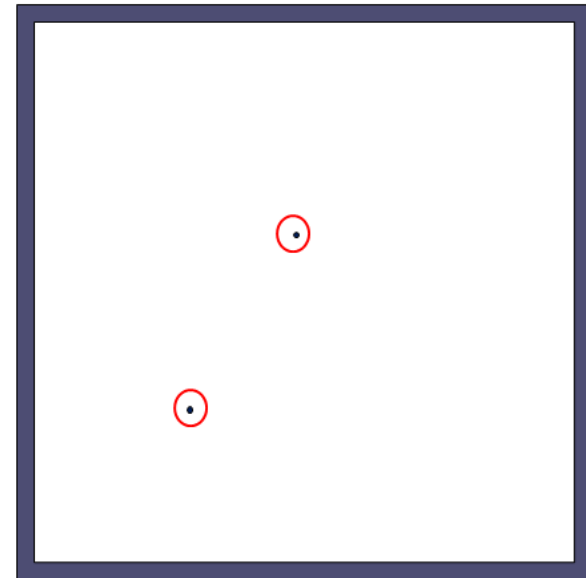
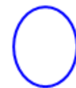
EUV Back Side Electrostatic-Chucked Defects Cleaning Capability

PRE $\geq$ 1 μm Defect Size POST







- Example of cleaning capability of Back Side E-chucked defects on EUV Masks
- Hard defects, pits or scratches, will not be cleaned by EL-C
- All removable defects larger than 1 micron were effectively removed by EL-C

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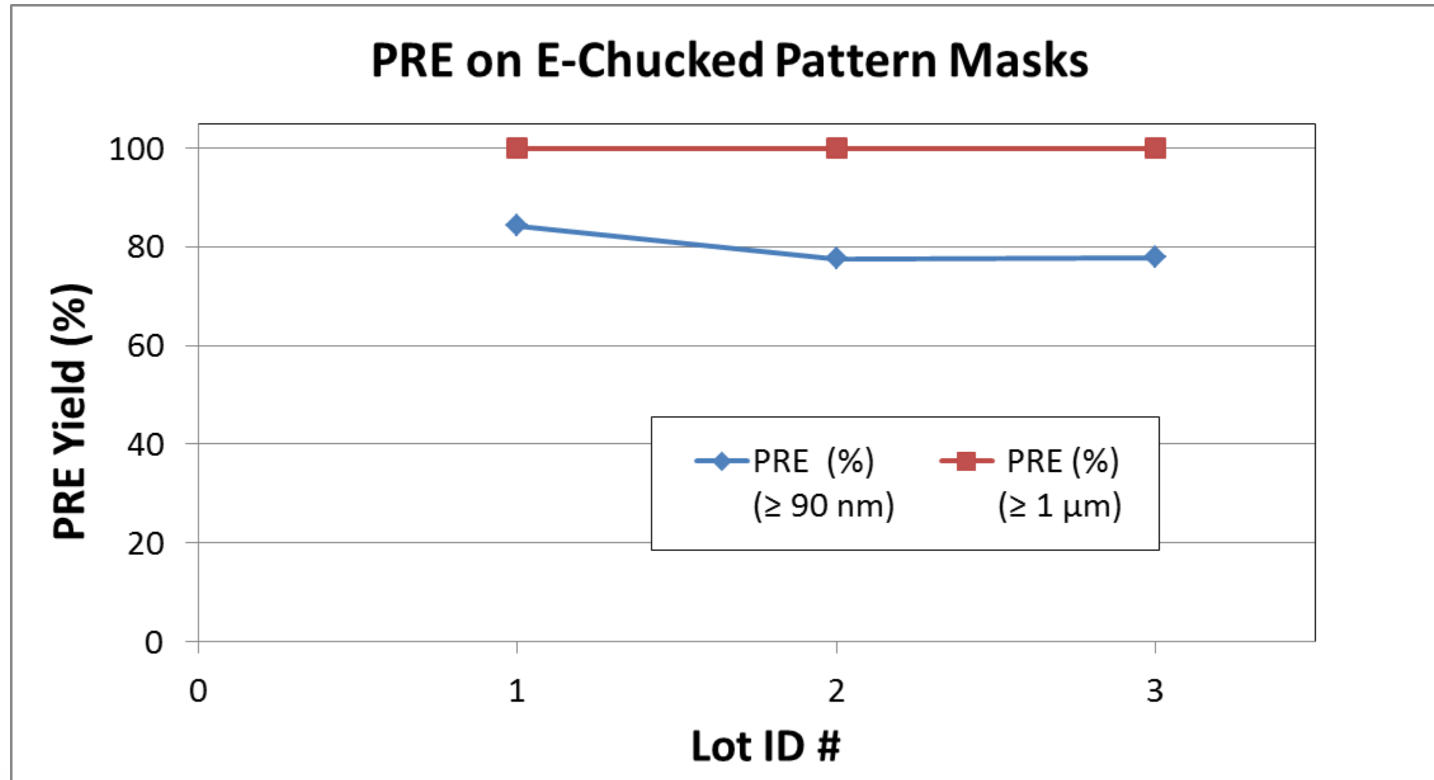
EUV Back Side Cleaning Capability

E-Chucked Defects on Production EUV Pattern Masks



- Cleaning capability of Back Side E-chucked defects on Production EUV Masks
- Hard defects, pits or scratches, will not be cleaned by EL-C
- All removable defects larger than 1 micron were effectively removed by EL-C

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Remarks and Conclusions

- CO_2 Cleaning is in Production for Advanced Node Optical Masks at multiple customer sites
- CO_2 Cleaning is qualified on Production EUV pattern masks for backside E-chucked defects
- No mask degradation as a result of 50x CO_2 Cleaning
- Multiple cleaning applications have been identified and developed with CO_2 cleaning

CO_2 Cryogenic Aerosol Cleaning is production ready for EUV mask cleaning applications

Acknowledgements

- Charles W. Bowers and colleagues at Eco-Snow Systems

- Captive Mask Shop Customers

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Thank You

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