Cleaning Efficiency Improvement Solutions for FEOL CMP

Business of Cleans / SPCC Conference

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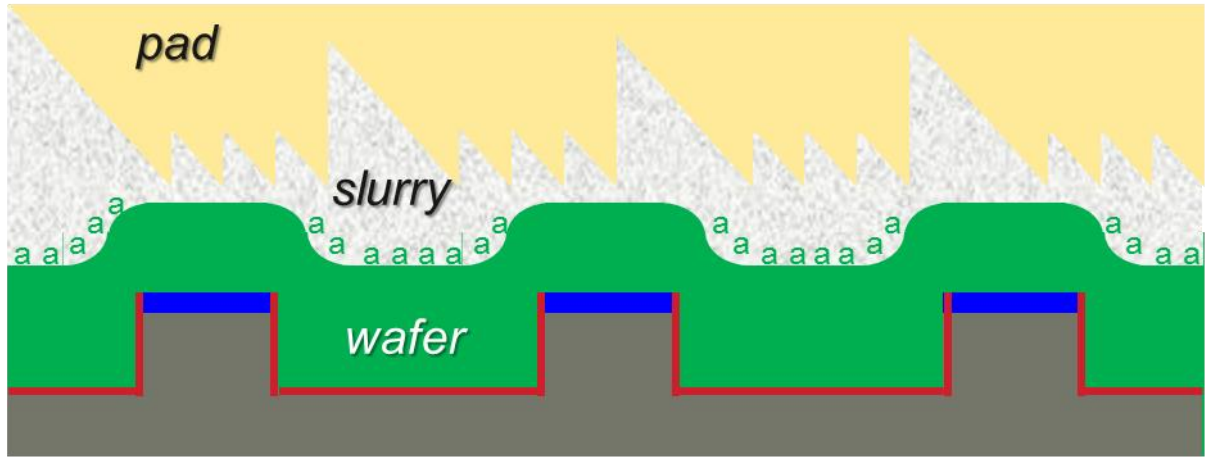
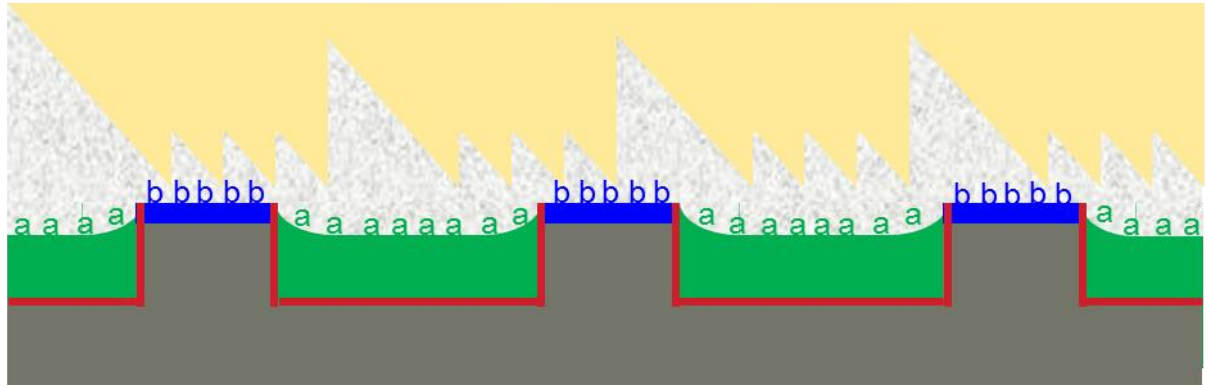
CMP Mechanism and Cleaning Challenges

- Three-body interaction: Wafer, Pad, Slurry
- Slurry: Complex suspensions containing abrasive particles, stabilizing agents and inhibitors
- Pad & abrasive remove inhibitor(a) from high pressure areas
- Remaining inhibitor(a) protects low areas.
- After polish layer cleared from stop layer, inhibitor(b) protects stop area and inhibitor(a) represses dishing of oxide in trenches
- Polishing by-products (chemical reactants, agglomerated slurry and pad/conditioner debris) are present on wafer after polish and needs to be removed during post-CMP cleans

Bulk Polish



Clearing and Overpolish



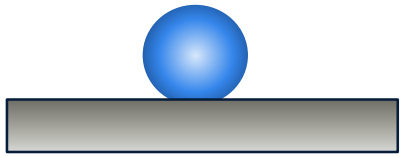
Particle Removal and Re-Deposition

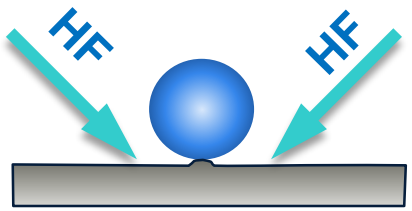
Particle Removal

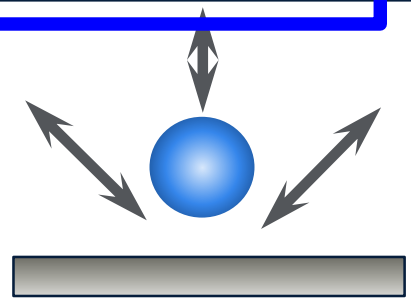
Particle attached on wafer surface

Breaking van der Walls forces:
- **Undercutting by HF**
- **Shear force by brush scrub, Megasonics, Fluid jet…**

Lift off by repulsive forces:
- **Shear force by brush scrub, Megasonics, Fluid jet…**
- **Electrostatic forces**







Particle Deposition

Van der Walls interactions: rapid deposition of particles close to the surface

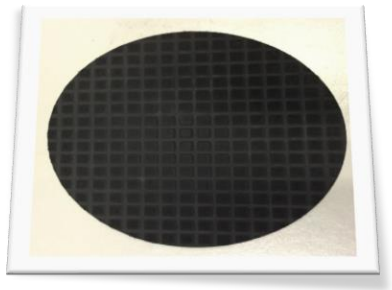
Diffusion of particles to surface due to overall attraction force and electrostatic force

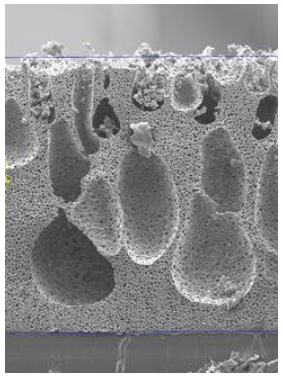
- Particle removal: interaction force between the particle and the substrate has to be eliminated by shear force:
  - Fluid shear flow, Brush scrub, Megasonic cleaning, Fluid jet
- Chemical etching is used to assist with breaking the particle-surface bond
  - Undercut on the substrate and/or wet etch of the particle
- After breaking the bond, the particle has to be removed away from the surface to prevent re-attachment

Post CMP Cleaning Trends

- **What stays the same? Key Post CMP Clean Technologies**

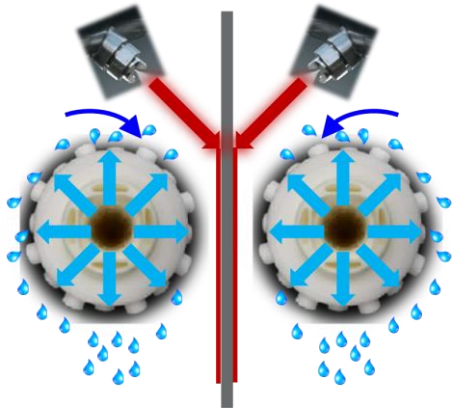
Chemical Mechanical Buff with Soft Pad





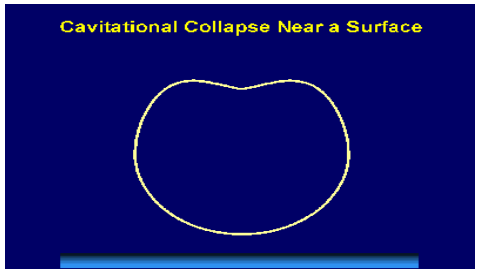
Highest shear force Chemical Clean
Goal: High PRE
Break particle-surface bond

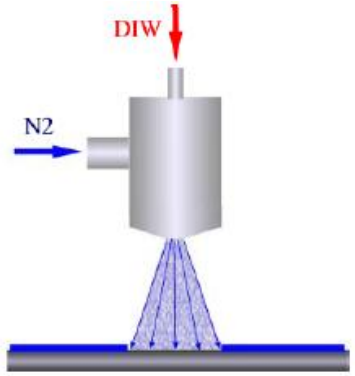
Double Sided Brush Scrub



High sheer force Chemical Clean
Goal: High PRE
Break particle-surface bond

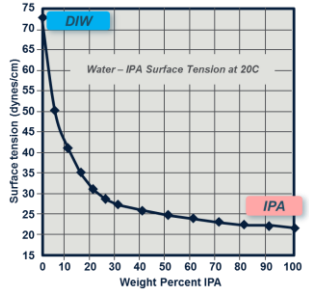
Non-Contact Cleans: Megasonic or Fluid Jet

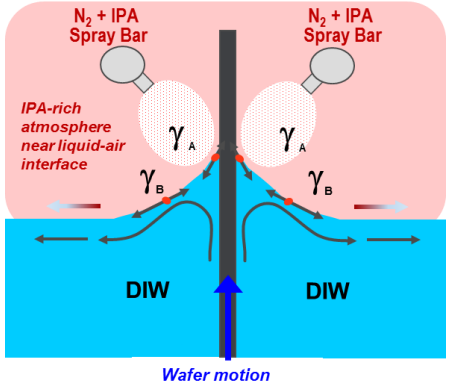




Low shear force Chemical Clean
Goal: Low adder
No re-contamination

Marangoni Dry





Surface tension gradient based drying
Goal: No adders
No watermarks

Post CMP Wet Clean (SPM)

Dehydration process:

$H_2SO_4 + H_2O_2 \rightarrow$

$\rightarrow H_2SO_5$ (Caro's acid) + H_2O

Formatioon of atomic oxygen

$H_2SO_4 + H_2O_2 \rightarrow$

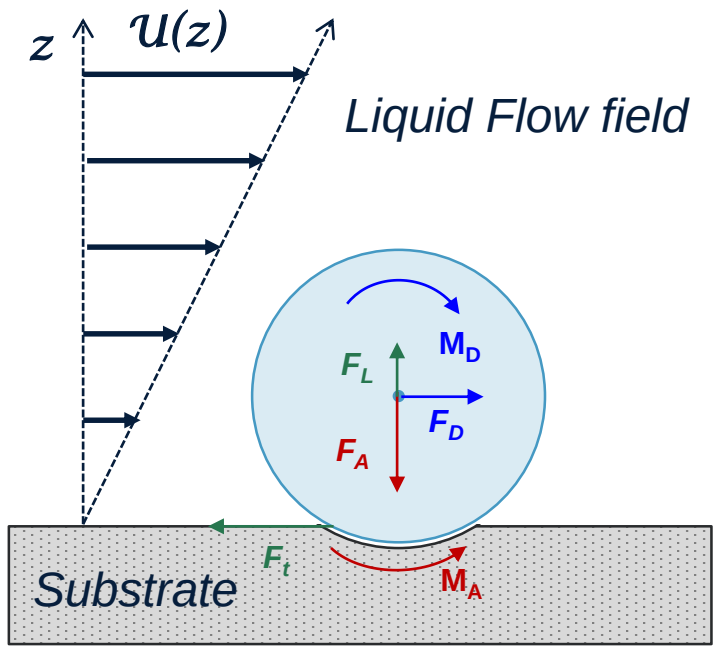
$\rightarrow H_3O^+ + HSO_4^- + O$

Aggressive Chemical Clean
Goal: Ce ion removal, Organics removal

Post CMP Cleaning Trends

- **What's Different? Clean Technologies' Implementation**
  - Decrease in the critical particle size drives more stringent cleaning efficiency requirements
    - Wide adoption of Chemical Mechanical Buff
      - "Easy to clean" applications now require cleaning efficiency improvements
        - PreClean™ initially adopted for FEOL; adopted in HVM for BEOL in 2018; great interested for WMG in 2019
    - Advanced metrology techniques
  - Novel Cleaning Chemistries drive HW compatibility specifications
  - Post CMP Wet Clean elimination: SPM replacement
  - Custom approaches and system flexibility requirements
    - Multiply films exposed require optimized module sequence and recipe structure
    - Tool box of Cleaning Options, which can be easily used based on specific applications and issues

Particle Removal

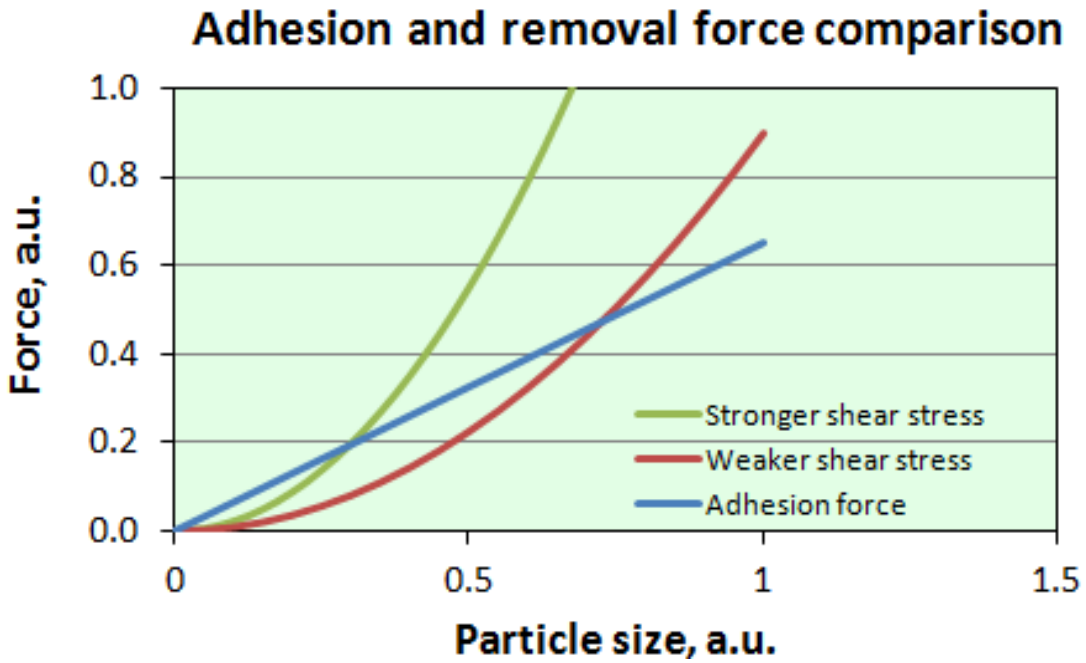


F_D – The Drag force
F_A – the Adhesion force
F_L – the Lift force
F_t – the tangential friction

$$MR = \frac{Removal(Drag)\ Moment}{Adhesion\ Moment}$$

For MR >1, a certain % of particles can be removed

- Adhesion moment
  - Function of adhesion force (van der Waals), particle geometry
  - Proportional to particle radius
- Removal Moment:
  - Function of shear force, double layer interactions, particle geometry
  - Proportional to square of particle radius



$$W_{vdw} = -\frac{\pi^2 C \rho^2 D}{12H}$$

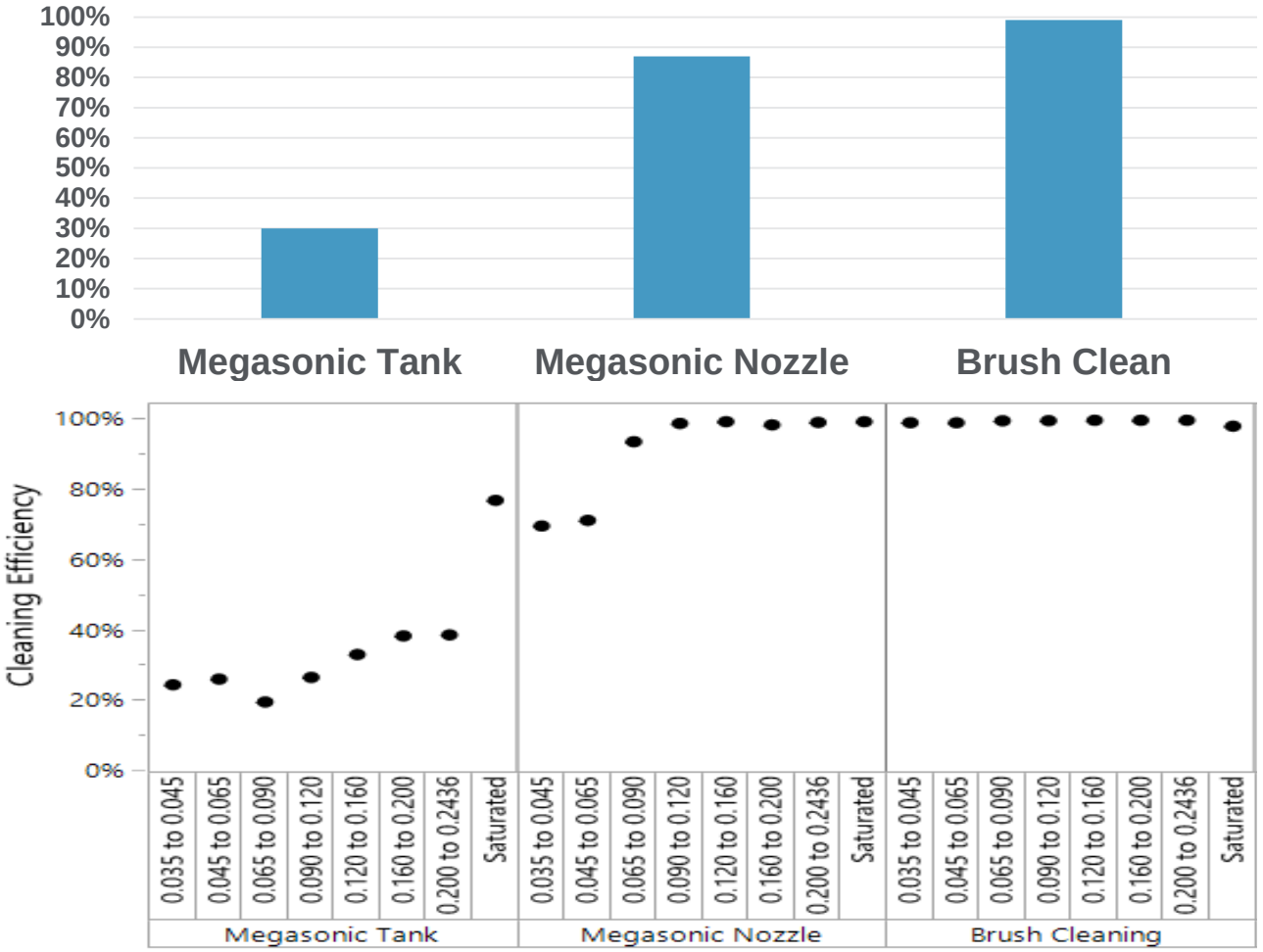
$$F_{drag} = 8\eta\dot{\gamma}_o(D)^2$$

η_s = shear viscosity

$\dot{\gamma}_0$ = shear stress

Smaller particles are more difficult to remove

Cleaning Efficiency Comparison on “Easy to Remove” Particles for Individual Cleaner Modules



$$\textit{Cleaning Efficiency} = \frac{(\textit{Pre} - \textit{Post})}{\textit{Pre}}$$

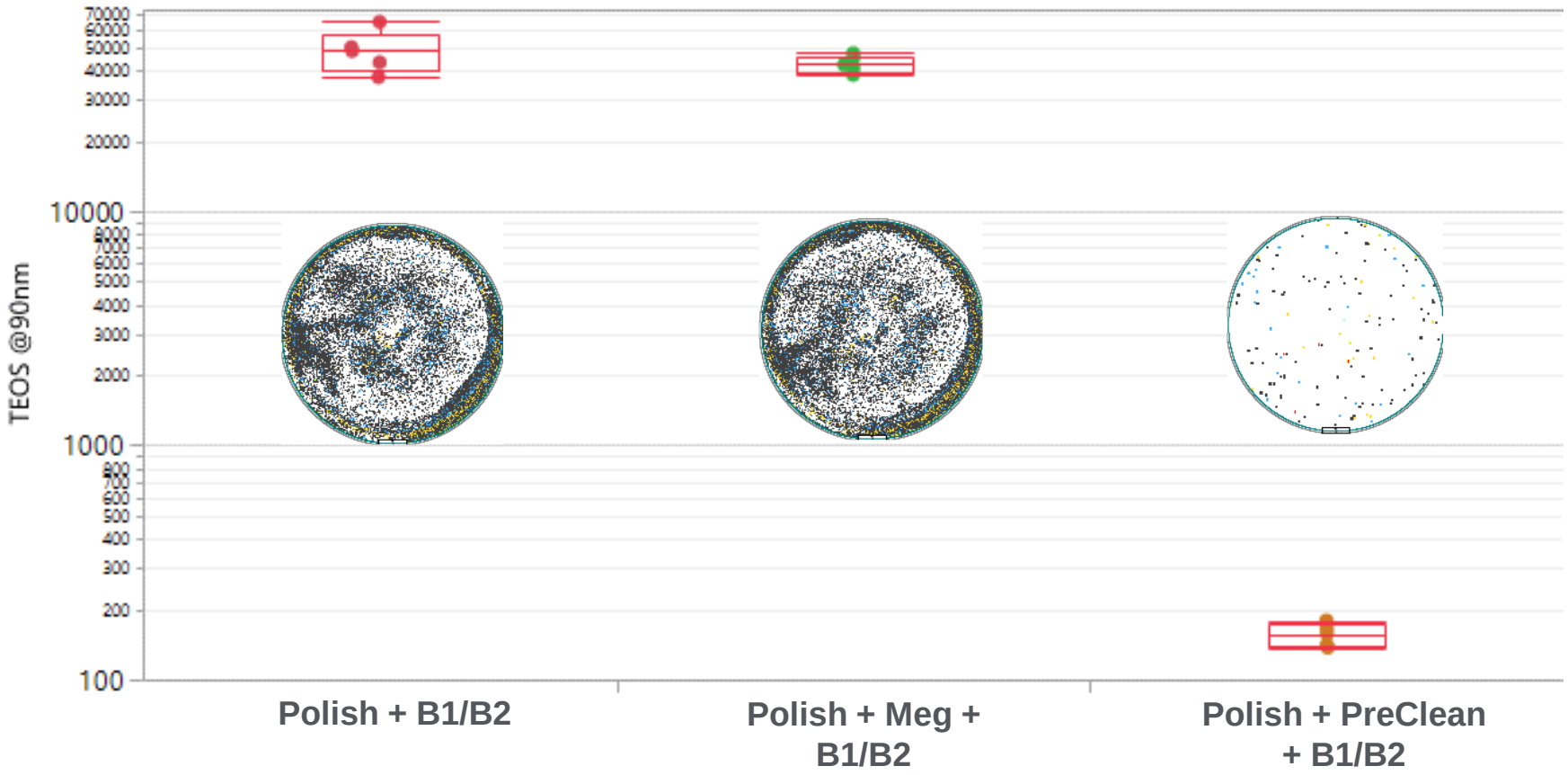
All modules run with < 2.0 wt% NH_4OH

Challenge wafers: Spin-on SiN particles on TEOS film

Contact Clean methods demonstrate high particle removal efficiency
Brush shear force is sufficient to remove >99% of the particles

APPLIED MATERIALS

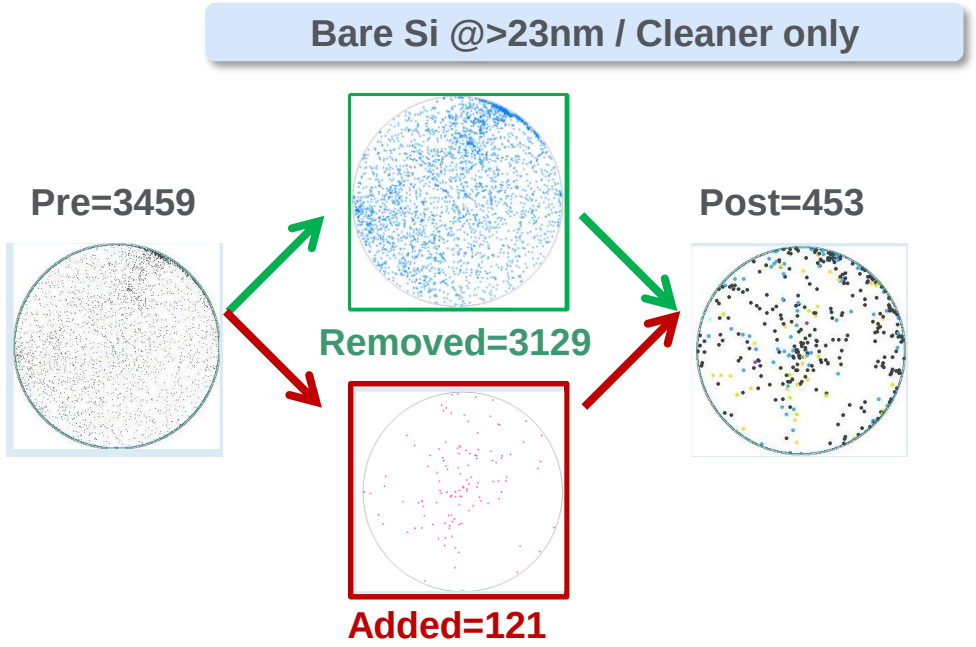
Cleaning Efficiency Comparison on Post CMP Defects



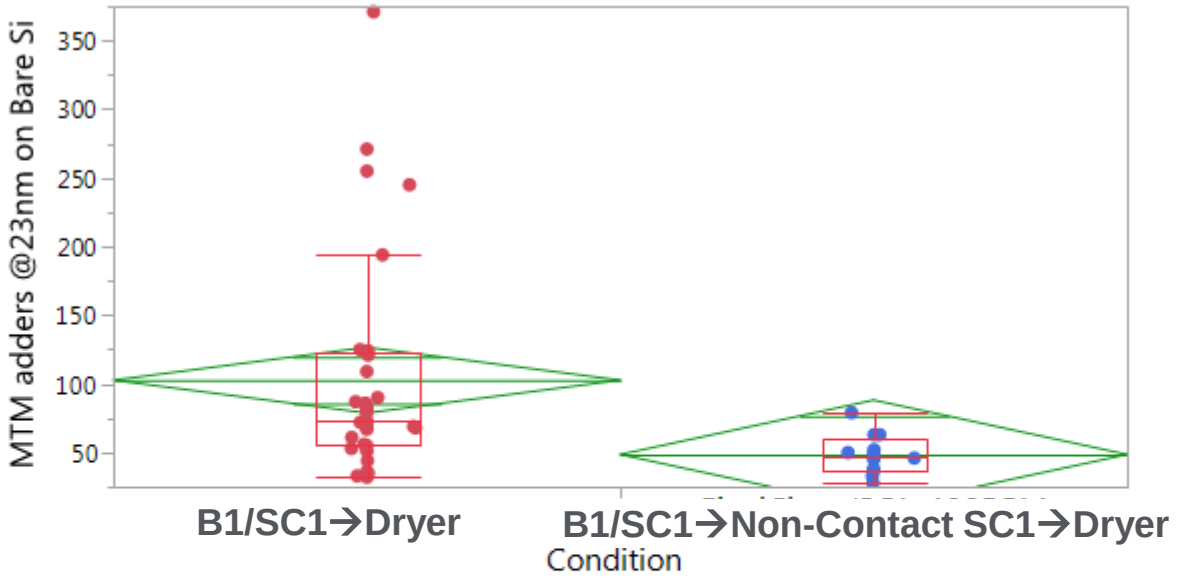
Brush shear force is NOT sufficient to remove strongly attached particles
Adding Chemical Mechanical buff in PreClean module improves defects >100X
Adding Megasonic tank clean does not improve defects

Polisher: Asahi Ce slurry / VP50xx pad / PreClean: Acidic Clean Chemistry / BKM pad / Meg:DIW, BB1:acidic clean, BB2:DIW

Why Non-Contact Clean is Needed?



Post = Pre - Removed + Added



Oneway Anova

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
B1/SC1	33	102.727	11.858	78.814	126.64
FinalClean/SC1_400RPM	12	48.583	19.664	8.928	88.24

Brushes scrubbing removes but also adds particles

Source of adders: Loose particles suspended in liquid boundary layer on wafer surface

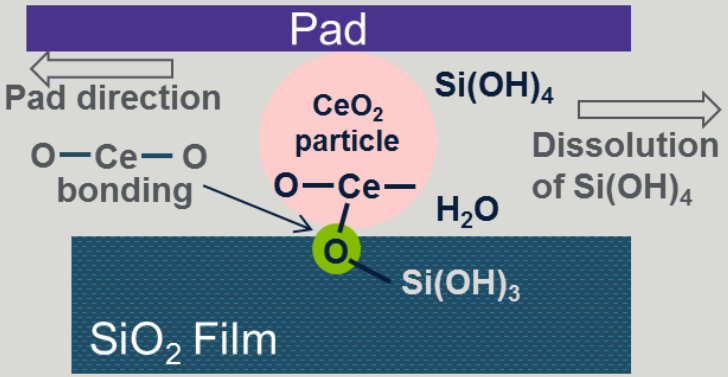
Non-Contact Clean after brush scrub reduces adders by 50%

Non-Contact Clean benefits:

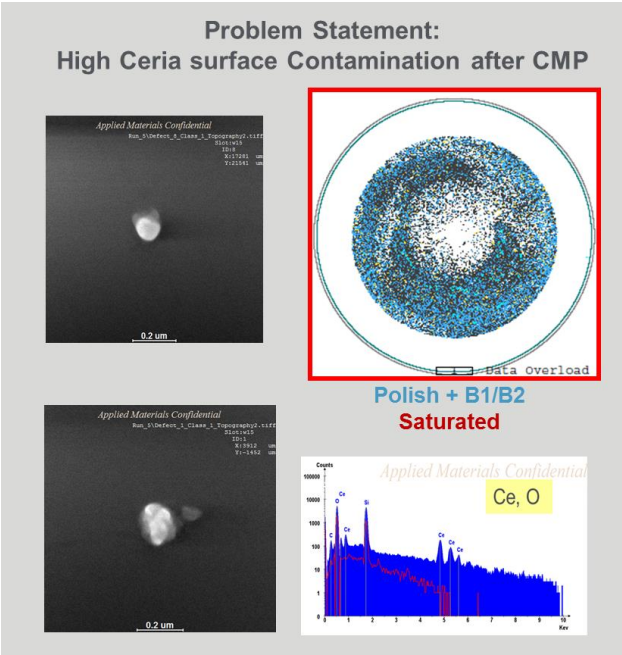
- When used before contact clean, Non-Contact Clean prevents media loading
- When used after the brush, Non-Contact Clean reduces re-contamination from brush

APPLIED MATERIALS

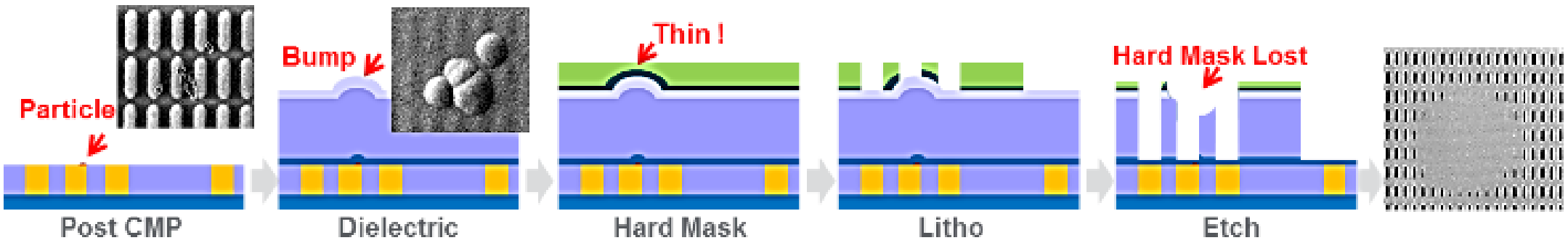
Ce Slurry Cleaning Challenge



- Ceria abrasive have significant surface chemical action during SiO_2 film polish



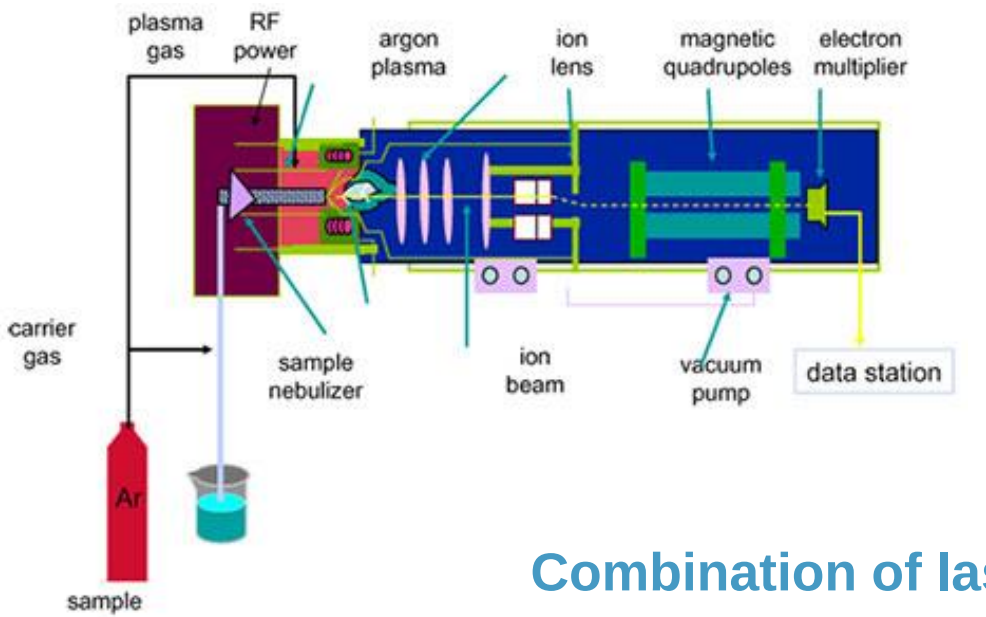
Slurry particle contamination remains high after conventional Brush Scrub



Nano-Particles (<50nm size) cause patterning issues at subsequent level (shorts, opens)

APPLIED MATERIALS

Advanced Metrology Techniques Needed to Detect Nano-Ceria



- ICP-MS Ce detection is a sensitive method to quantify Ce particle contamination below the SP5/SP7 sensitivity limits
- VPD ICP-MS analysis is a 3-step process:
  - Decomposition of oxide layer using HF vapor:
    - $SiO_2 + 6HF \rightarrow H_2SiF_6 + 2H_2O$
    - $H_2SiF_6 \rightarrow SiF_4 + 2HF$
  - Trace metals in oxide layer form water soluble fluorides; these are collected by scanning process
    - $Fe_2O_3 + 6HF \rightarrow 2FeF_3 + 3H_2O$
    - Cerium fluorides has poor flexibility. Specialty acid blend is used to ensure complete collection of Ce-containing compounds
  - Post scanning, VPD droplet is collected and analyzed by ICP-MS

Combination of laser scattering techniques (SP5/SP7) and ICP-MS is used for Ce Cleans development

Integrated Ceria Cleaning Solution

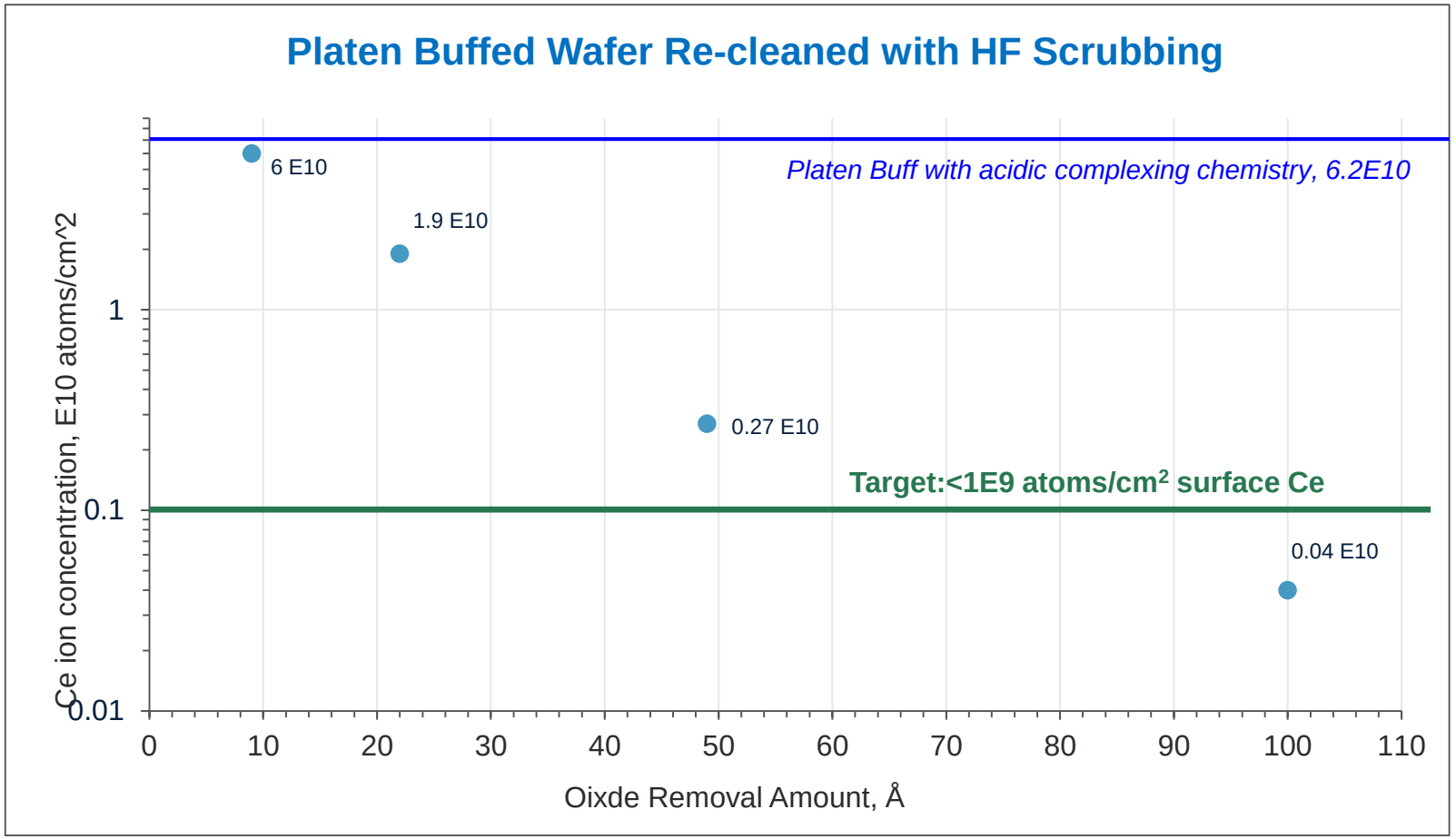
- Applied Materials is developing an integrated (within CMP cleaner) ceria cleaning solution *to eliminate post-CMP wet cleaning*
- Comparison

Challenges of Current Industry POR (post CMP wet clean process)		Benefits of Integrated non-SPM/non-HF Ceria Cleaning Approach
• SPM long process time:	~3min/wafer -> ~20wph/chamber -> 240wph/system (12 chambers/system)	• Eliminates need for post-CMP wet clean: cycle time, fab space & SPM/HF CoC • Avoids additional handling and facilities requirements of SPM for CMP systems
• Additional integration step	required longer cycle time & fab floor space	
• Hazard / Toxic of hot SPM/HF	required additional handling & facilities requirements	
• Cost of Hot SPM Usage	SPM CoC = raw material + waste treatment + handling within the fab	

Applied is focused on an Integrated non-SPM/non-HF Ceria Cleaning Solution

Non-HF Solution is Needed to Replace SPM Cleans

Post CMP Ce Removal Screening: HF Brush Scrub

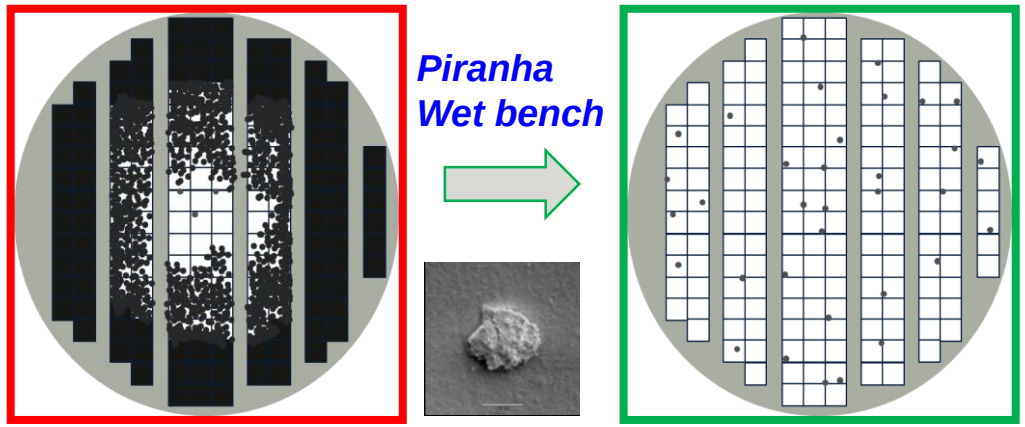


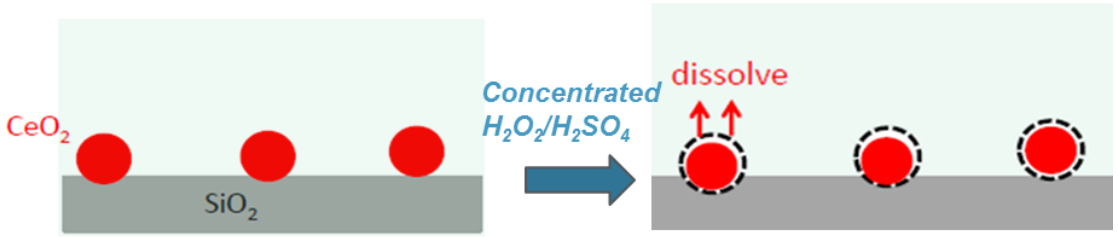
~70A TOX removal is needed to reduce Ce concentration to <1E9 atoms/cm^2 with HF scrub

HF is a poor choice for post CMP ceria removal

Ce Slurry Cleaning Challenge for High Oxide Removal CMP

Post CMP Piranha Clean can dissolve Ceria particles

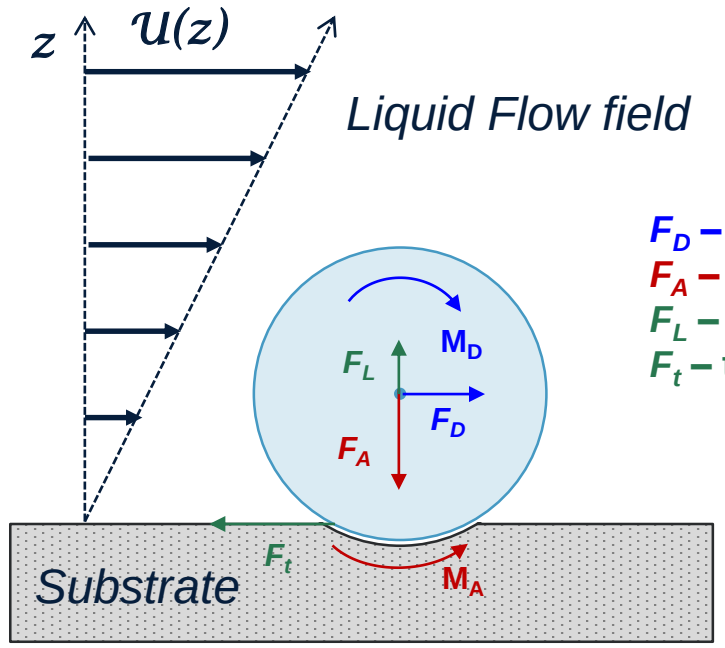




$$2\overset{+4}{\overbrace{Ce}}O_2 + H_2\overset{-1}{\overbrace{O_2}} + 3H_2SO_4 \rightarrow \overset{+3}{\overbrace{Ce_2}}(SO_4)_3 + \overset{0}{\overbrace{O_2}} + 4H_2O$$

$+1e^-$ $\quad$ $-1e^- X2$

Peroxide acts as a reducer in an acidic media and as an oxidizer in a basic media. In SPM, ceria is reduced by peroxide



F_D – The Drag force
F_A – the Adhesion force
F_L – the Lift force
F_t – the tangential friction

$$MR = \frac{Removal(Drag)\ Moment}{Adhesion\ Moment}$$

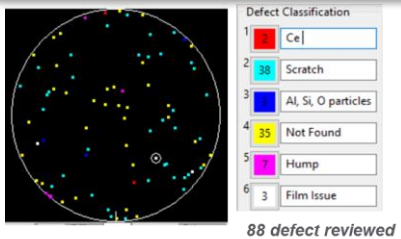
For MR >1, a certain % of particles can be removed

AMAT approach: replace chemical reaction with chemically assisted high shear force cleaning

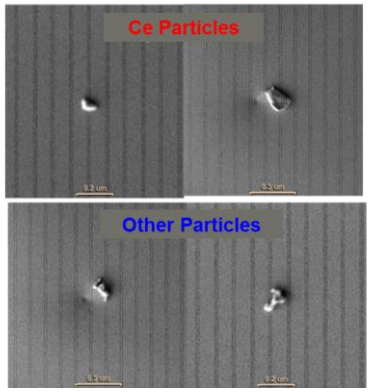
Integrated Ceria Cleaning Solution

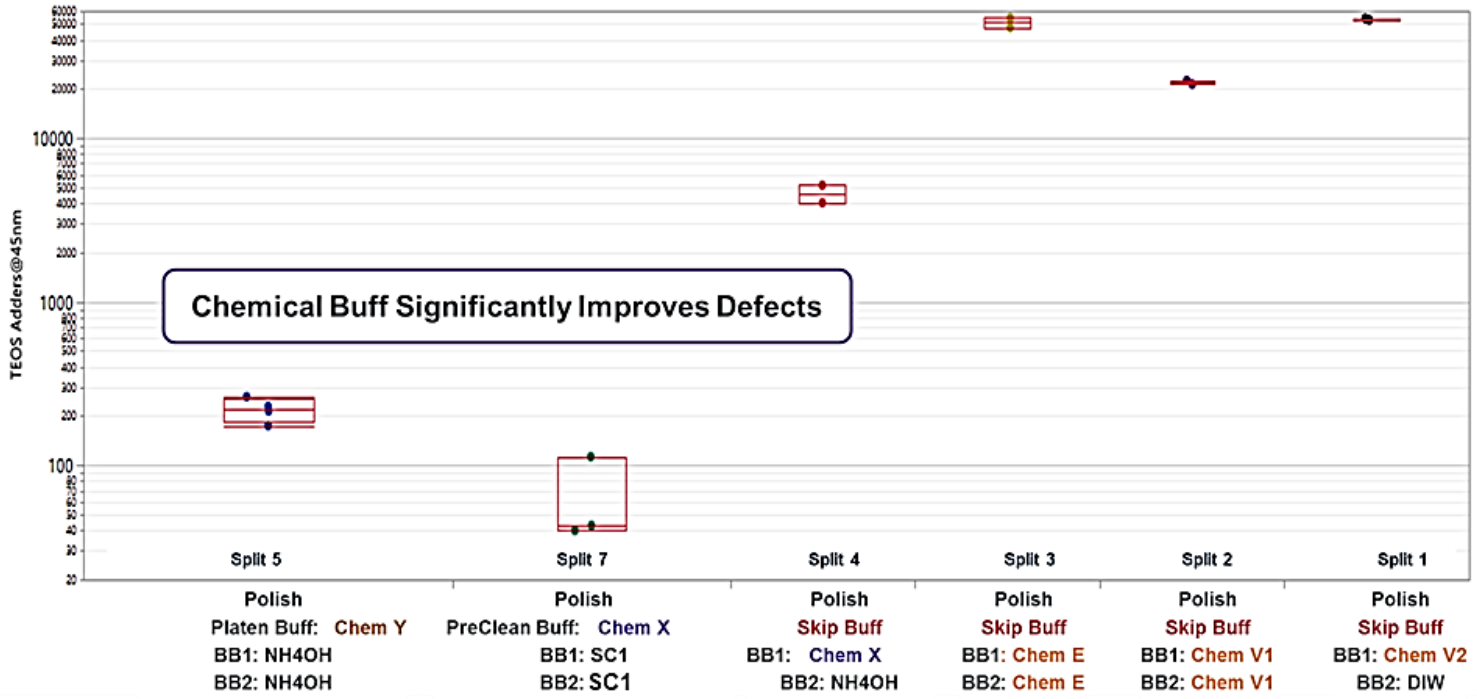
Split	Brief conditions	SP5 @45nm	Ceria Particles (defect review/ classification)	Notes
1-4 (No Buff)	Polish & Brush Box w/ Range of Cleaning Chemistries	20,000 to 50,000	>200 (est.)	Chemistries can help, but not sufficient
5	Polish w/ Platen Buff w/ Chem Y	180 to 280	Did not measure	High PRE Buff makes significant improvement
6	Polish w/ PreClean w/ Chem Y	215	4	PreClean Shows Similar Performance to Platen Buff
7	Polish w/ PreClean w/ Chem X	127	None Found	Chemistries in PreClean can impact performance

Split 6 Previous BKM PreClean w/ Chem Y

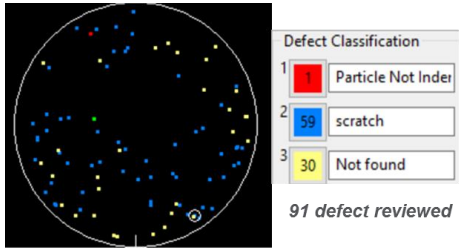


88 defect reviewed





Split 7 CnF PreClean w/ Chem X



91 defect reviewed

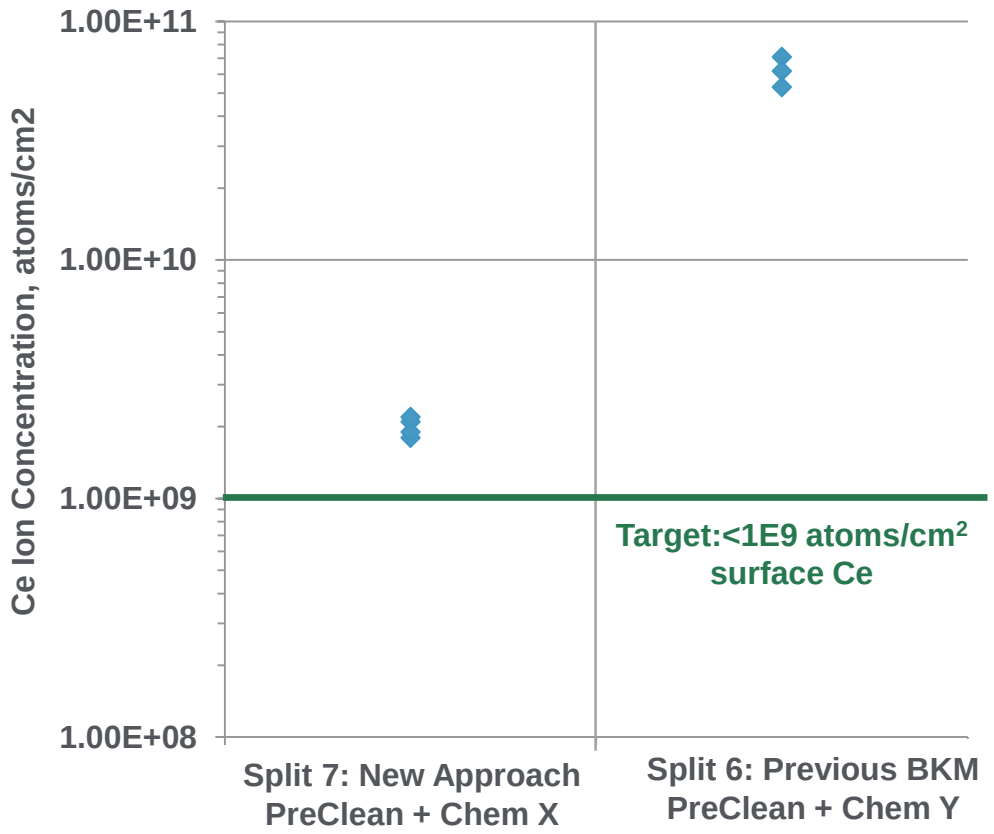
C&F of a Non-SPM/Non-HF Integrated Ceria Cleaning Solution

Versum STI24xx / Nexplanar 60YY Polish

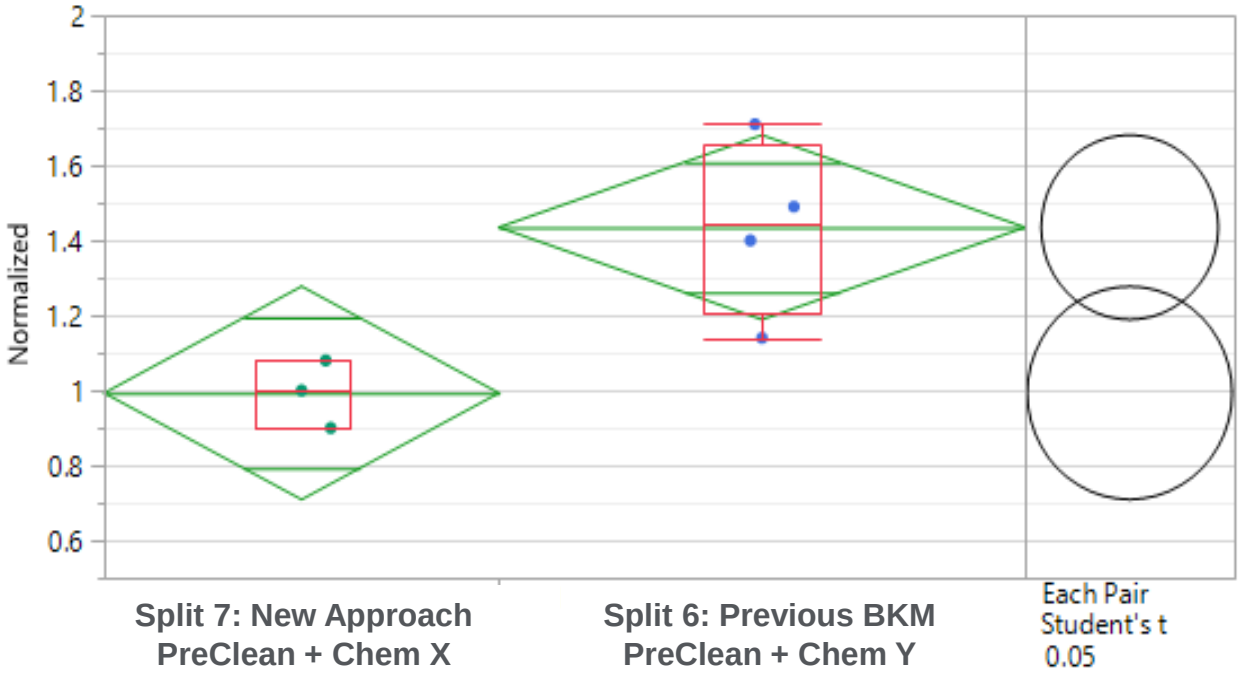
APPLIED MATERIALS

Non-SPM Clean Performance

Ce Ion Concentration by VPD ICP-MS



Defects by SP5



Means and Std Deviations

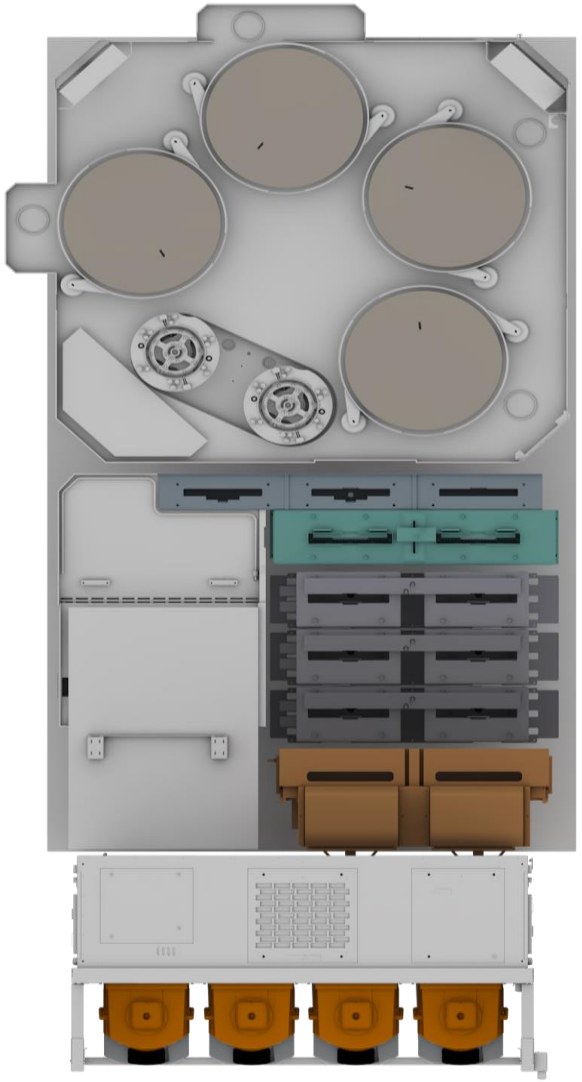
Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Split 7: New Approach	3	0.99333	0.090185	0.05207	0.7693	1.2174
Split 6: Previous BKM	4	1.43500	0.235867	0.11793	1.0597	1.8103

10-15X improvement in Ce ion surface concentration with new approach
50% improvement in defect performance on TEOS

Versum STI24xx / Nexplanar 60YY Polish

APPLIED MATERIALS

Addressing Post CMP Cleaning Challenges in LK Prime™ System



- Cleaner: 5x Side-by-Side Cleaner Stations
  - Megasonics
    - Provides physical force to remove contamination form the features
    - Provides full wafer immersion tank for bevel contamination removal
  - PreClean
    - Provides means to perform chemical buff in a dedicated slurry-free module
    - Vertical buff enables effective contamination removal off the surface
    - Enable cleaning of top surface of the wafer bevel
  - Two consecutive brush boxes provide high particle removal efficiency and precise brush pressure control
  - Vapor Dryer provides defect-free drying of hydrophilic, hydrophobic and mixed surfaces
  - Cleaner Chemical Flexibility enables particle undercut and lift-off
    - HF-compatible brush box enables SiO_2 substrate etching
    - Proprietary chemicals often include particle etch capability

AMAT CMP Defect Improvement Tool Box

Module	Feature	Benefit	Mechanism
HCLU	Chemical Rinse during polish to clean transition	Improved defectivity for Poly / Si CMP	Improved wetting on hydrophobic films (Poly, BDIII)
PreClean	Soft Pad buff	Significant reduction in defects	Particle removal efficiency with high shear force
Brush Box	Specialty Spray Bars	Edge signature excursion control	Optimized chemical distribution to wafer edge
	SteadyClean	Excursion control Brush life improvement	Consistent sheer force over brush life
	BB2.0	Excursion control Brush life improvement	In-situ brush cleaning
	HF/Ozone BB	Significant reduction in defects for HF-Last CMP	Surface conversion Organics reduction
	Multistep BB recipe	Reduction in defects	Combination of brush open/ close steps
Dryer	VD1.5	TPT Improvement	N2/IPA Spray optimization

Ready to Engage to Develop/Optimize a BKM for Customers (i.e., your wafers and consumables)

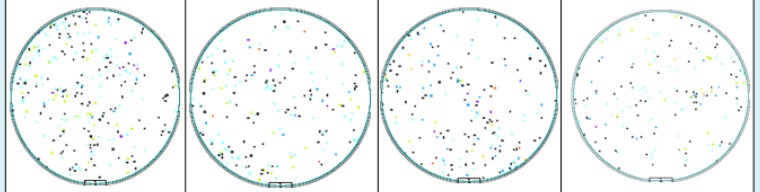
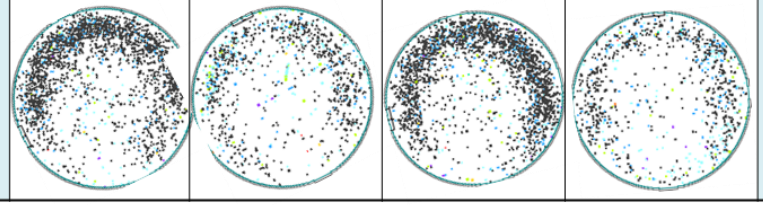
Chemical Rinse in HCLU: Poly CMP

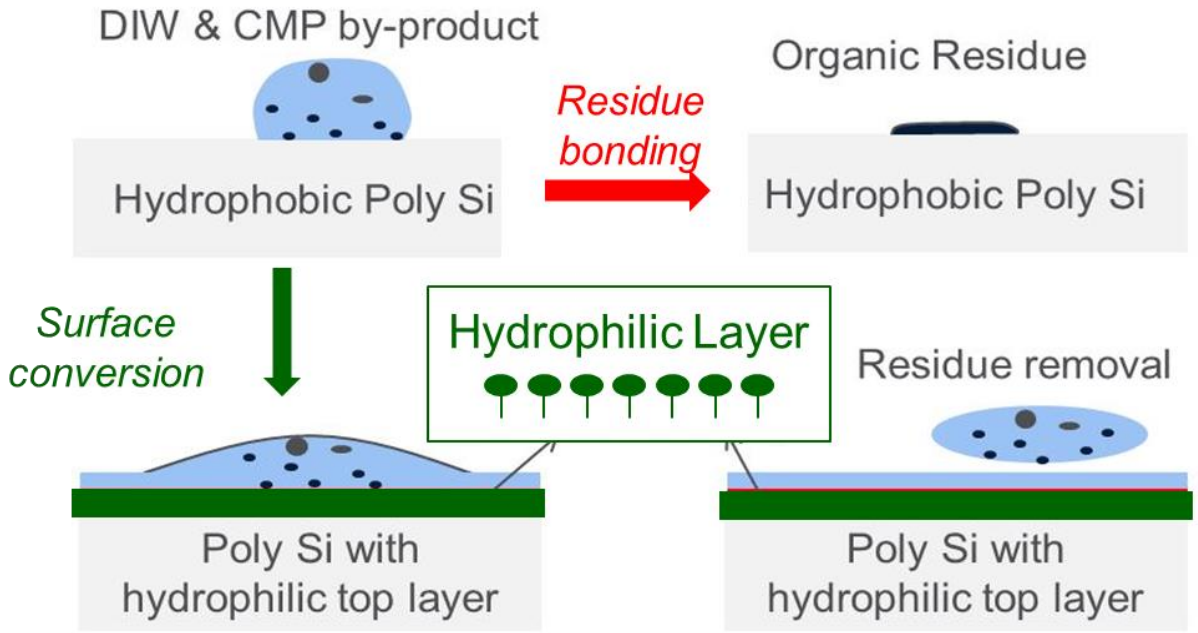
Objective:

- Convert Hydrophobic poly surface to Hydrophilic as soon as possible after polish step to prevent strong bonding of residues onto surface

Strategy:

- Rinse wafer surface in HCLU with surfactant-containing cleaning chemistry

Process	SP2 Maps	SP2 Maps	SP2 Maps	SP2 Maps	Ave. Counts@ 80nm
Polish_1psi 60s_ HCLU 10s Chemical Rinse_ PreC Buff_MegB1B2					164
Polish_1psi 60s_ HCLU 10s DIW Rinse _ PreC Buff_MegB1B2					1654



About 10X improvement in defects from adding chemical rinse in HCLU was observed

Polish: Silica slurry polish / HCLUl: acidic cleaning solution / PreClean: acidic cleaning solution

PreClean Module for Chemical Mechanical Buff

Challenge:

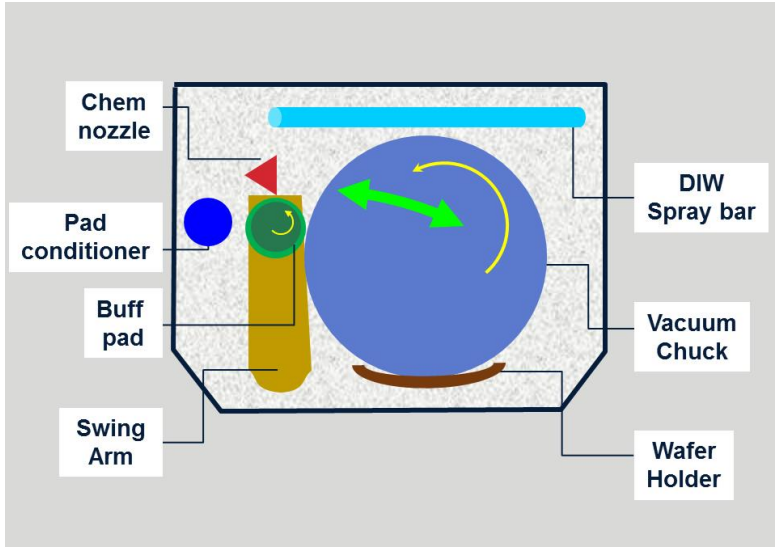
- Nano-Particles (<50nm size) cause patterning issues at subsequent level (shorts, opens)
- Buffing in polisher impacts TPUT

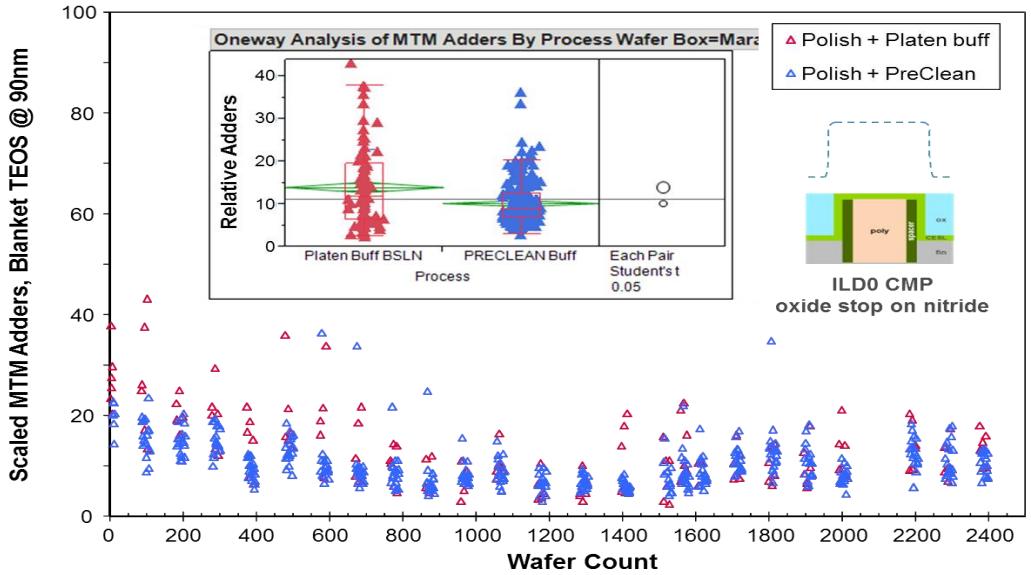
Approach:

- Move chemical buffing from polisher to cleaner
- Vertically orient to leverage one-pass chemical usage and avoid particle re-attachment and scratching

Applied's Solution:

- **Soft Pad Chemical Buff in the Cleaner**



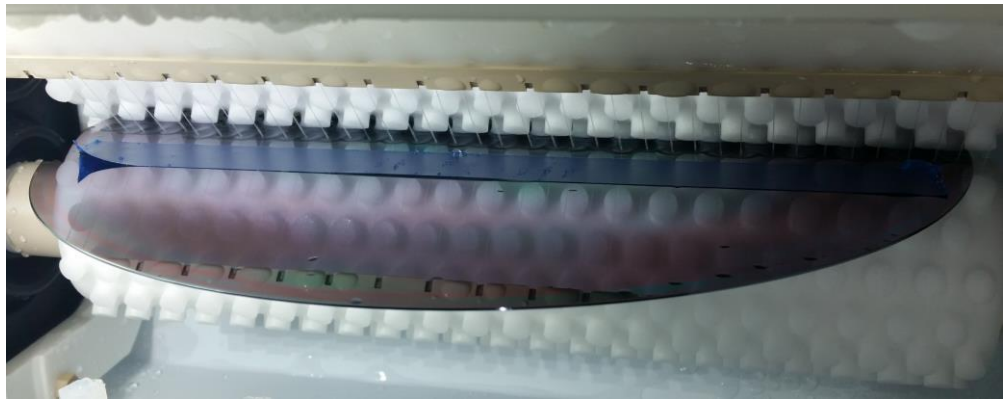


P1: Asahi ceria slurry, Vision pad; P2/PreClean: Fujimi acidic chemistry, DIW Meg; BB1: CX100; BB2: DIW

Chemical Mechanical Buff with optimized chemistry is needed for FEOL CMP

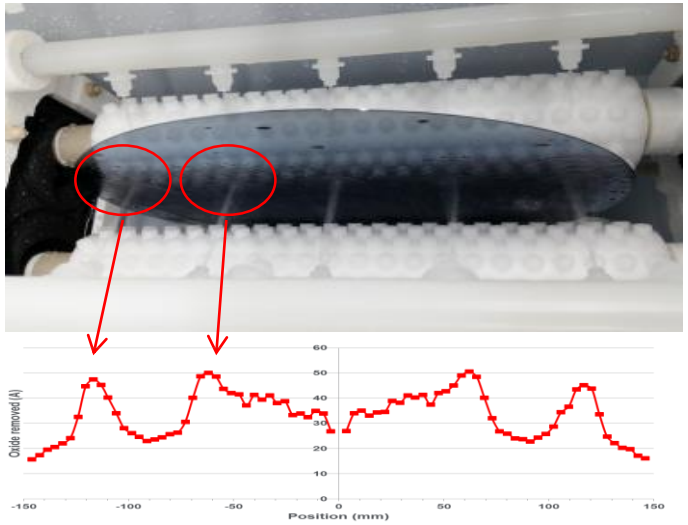
Brush Box Spray Bar CIP

Chemical Coverage Uniformity Improvement



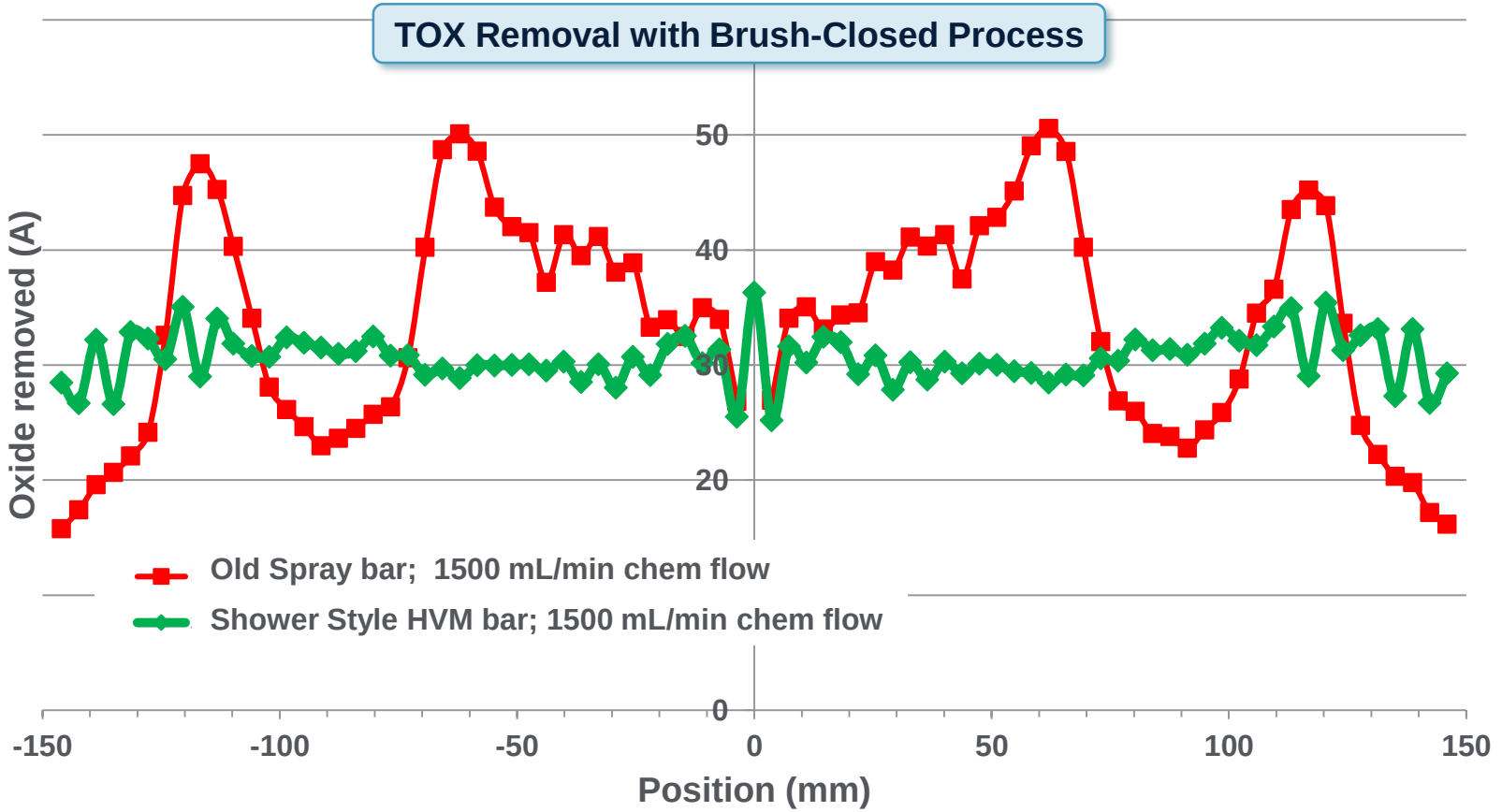
Problem Statement

- Chemical etch (coverage) non-uniformity with brush-closed process due to brush and chemical spray interferences



Solution

- Optimized shower style spray bar



Shower style HVM spray bar improves range by 3X

Released for LK Prime™ and LK3.0

APPLIED MATERIALS

Ozonated Water Clean for Oxide and Poly Polish

Organics Reduction

Objective:

- Remove organic contamination with Ozonated Water Clean

Strategy:

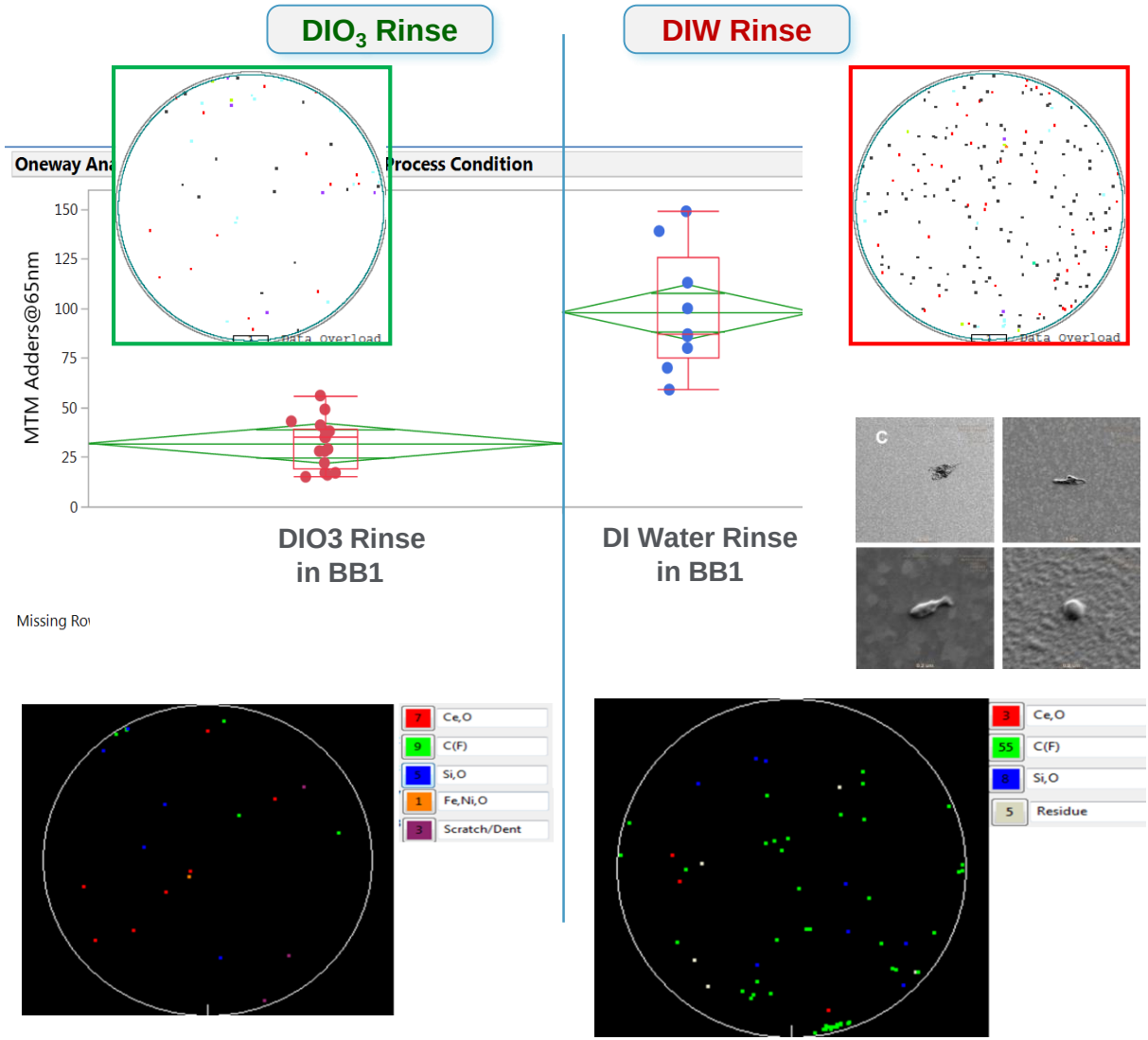
- Implement DIO_3 rinse in Brush Box (BB1 or BB2)
- Supply DIO_3 through DIW rinse spray bars
- Reduce O_3 concentration to <10 ppm for brush compatibility
- Remove brushes to eliminate interactions with DIO_3 if higher O_3 concentration is needed

Status:

- Implemented in Si CMP BKM: NH_4OH + HF/DIO3
- Released for LK Prime™

Defect reduction with DIO_3 is due to reduction in surface Carbon and Si surface conversion

DIO_3 Rinse in BB1, Prior to Chemical Scrub



3x improvement observed with DIO_3

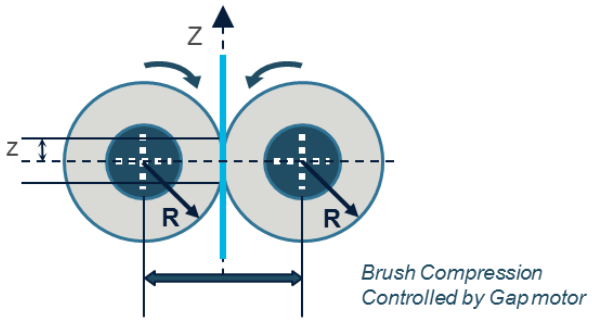
SteadyClean: Advanced Brush Torque Control

Challenge :

- For small brush gap compression processes (<0.5mm), variations in roller brushes & mechanical setup lead to unstable particle cleaning and/or short brush lifetimes.

Approach:

- Maintain consistent brush shear force on wafer surface by dynamically changing brush spacing to keep brush motor torque consistent

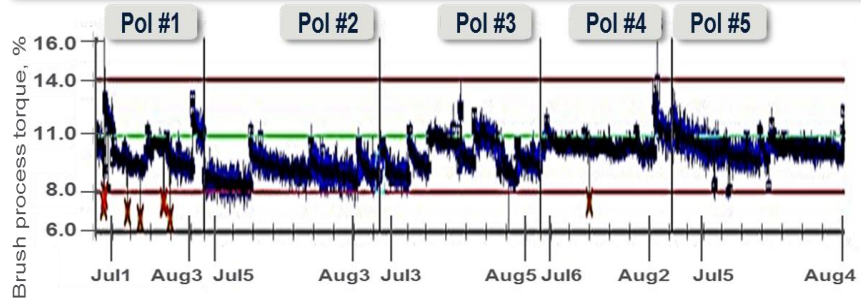


Benefit:

- Consistent brush PRE for **stable particle defect** performance and **longer brush lifetimes**.

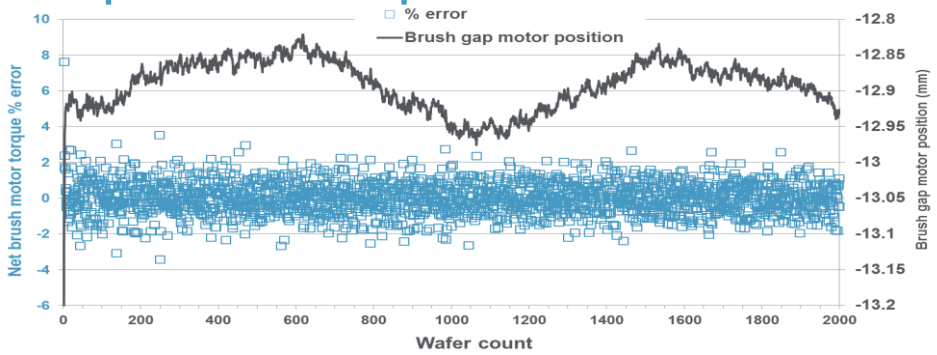
Control Shear Force for Consistent Roller Brush PRE

Challenge: Brush Shear Force Fluctuations

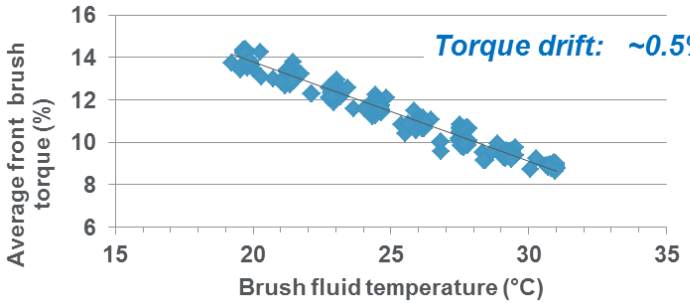


Approach: Consistent Brush Motor Torque

Keeps net brush torque stable over 2000+ wafers



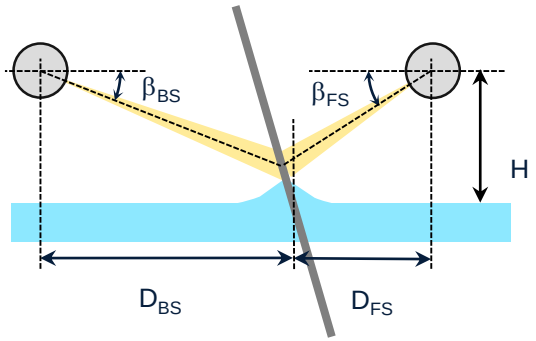
Compensates for environmental changes by dynamically changing brush spacing



Vapor Dry 1.5

- **Objective:**
  - High speed vapor drying process to support short polish times
  - More robust Drying
- **Strategy:**
  - Optimized spray bar position and angle as well as N2-IPA flow
  - Modified angle, height and spacing of spray bars to front and back
- **Status:**
  - 29 sec BKM with new bars equivalent to 52 sec BKM with old bars
  - **Available on LK and LK Prime™**

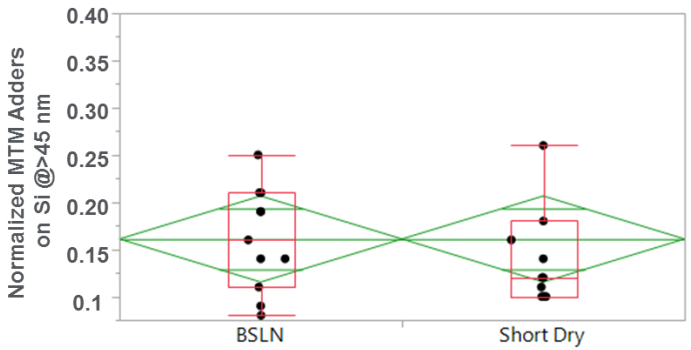
Residual water



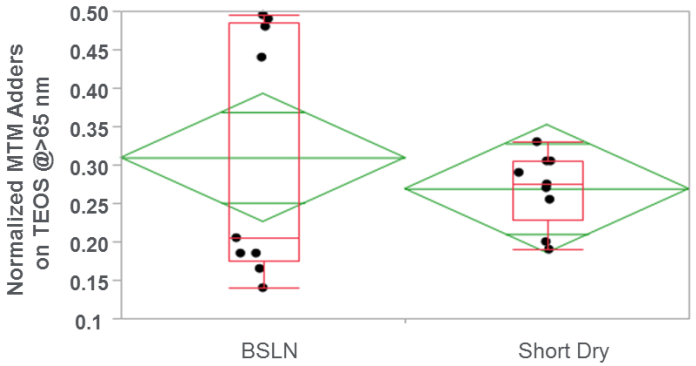
Inputs
- Angle
- Height
- Distance
- N_2/IPA flow rate

Outputs
- Defects
- Wetness
- Touch-point

Si @ 45nm



TEOS @ 65nm



Optimized IPA spray bar (VD1.5) enables high speed dry on hydrophilic substrates

CMP Defect Improvement Tool Box

Module	Feature	Benefit	Mechanism
HCLU	Chemical Rinse during polish to clean transition	Improved defectivity for Poly / Si CMP	Improved wetting on hydrophobic films (Poly, BDIII)
PreClean	Soft Pad buff	Significant reduction in defects	Particle removal efficiency with high shear force
Brush Box	Specialty Spray Bars	Edge signature excursion control	Optimized chemical distribution to wafer edge
	SteadyClean	Excursion control Brush life improvement	Consistent sheer force over brush life
	BB2.0	Excursion control Brush life improvement	In-situ brush cleaning
	HF/Ozone BB	Significant reduction in defects for HF-Last CMP	Surface conversion Organics reduction
	Multistep BB recipe	Reduction in defects	Combination of brush open/ close steps
Dryer	VD1.5	TPT Improvement	N2/IPA Spray optimization

Ready to Engage to Develop/Optimize a BKM for Customers (i.e., your wafers and consumables)

Summary

- Geometry shrinking and new material implementation in advanced nodes demand the achievement of high particle removal efficiency
- To address cleaning challenges in various nodes, Applied CMP Clean technology continues to evolve and includes broad portfolio of cleaning techniques
  - Optimized post polish rinse
  - High shear force PreClean module for high particle removal efficiency
  - Single wafer Megasonic module for improving defect removal efficiency
  - HF-compatible dual brush box module with
    - Improved chemical coverage uniformity
    - SteadyClean Brush Torque (Shear Force) Control for Consistent Roller Brush PRE
    - Ozonated Water Rinse for Organic Defect Reduction
    - BB2.0 Brush Conditioning for Extended Brush Life
  - Single wafer IPA dryer for achieving water-mark free drying at high speed (with VD1.5 option)

Optimized Solutions Require the Right Approach (Process Modules) and the Right Process (Process Engineers/Applied)


APPLIED
MATERIALS®
make possible