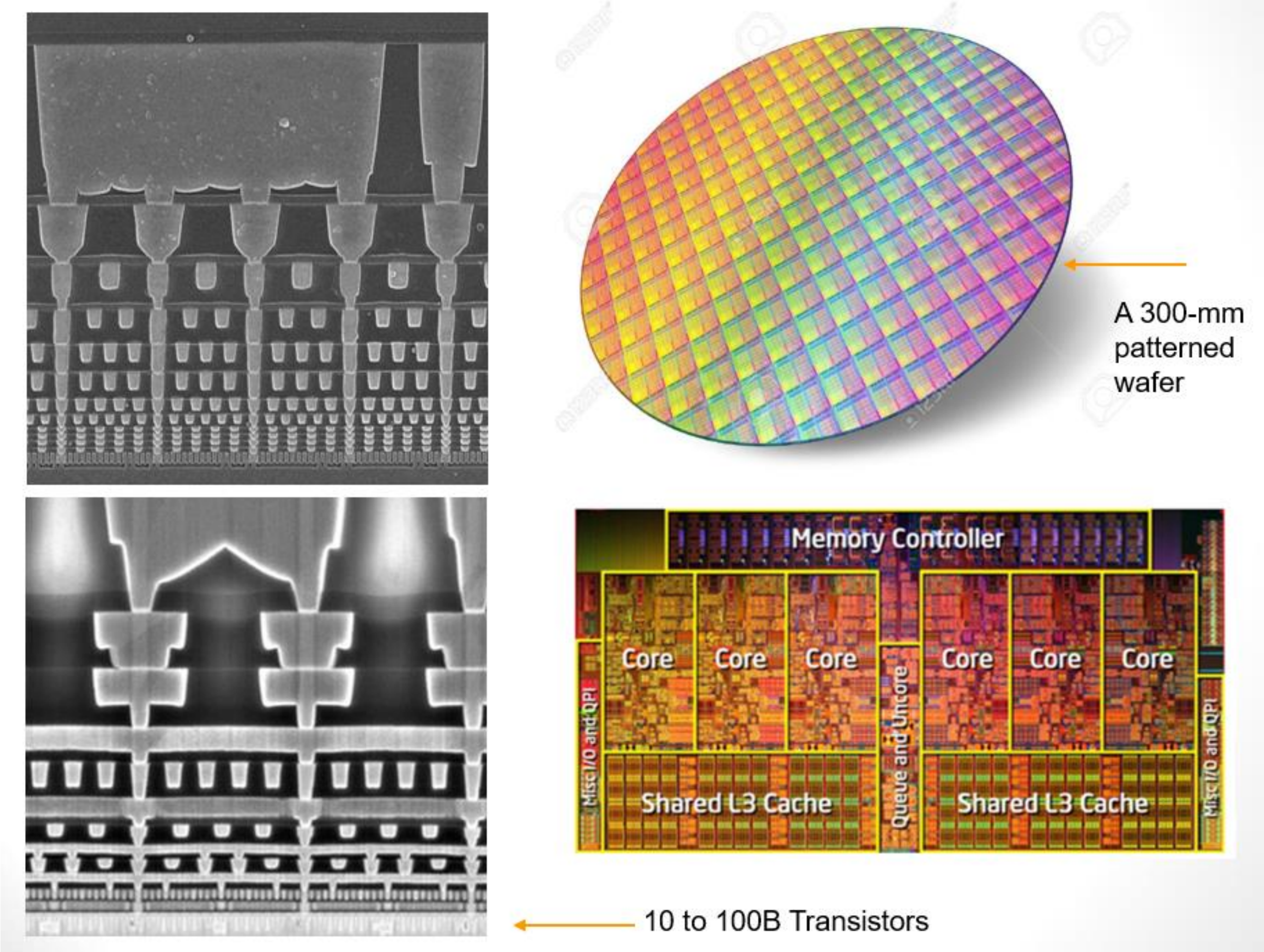
Reducing Slurry Consumption While Boosting CMP Process Performance

Ara Philipossian [1, 2], Yasa Sampurno [1] and Jason Keleher [3]

[1] Araca, Inc. Tucson AZ USA
[2] University of Arizona, Tucson AZ USA
[3] Lewis University, Romeoville, IL USA

Chemical Mechanical Planarization

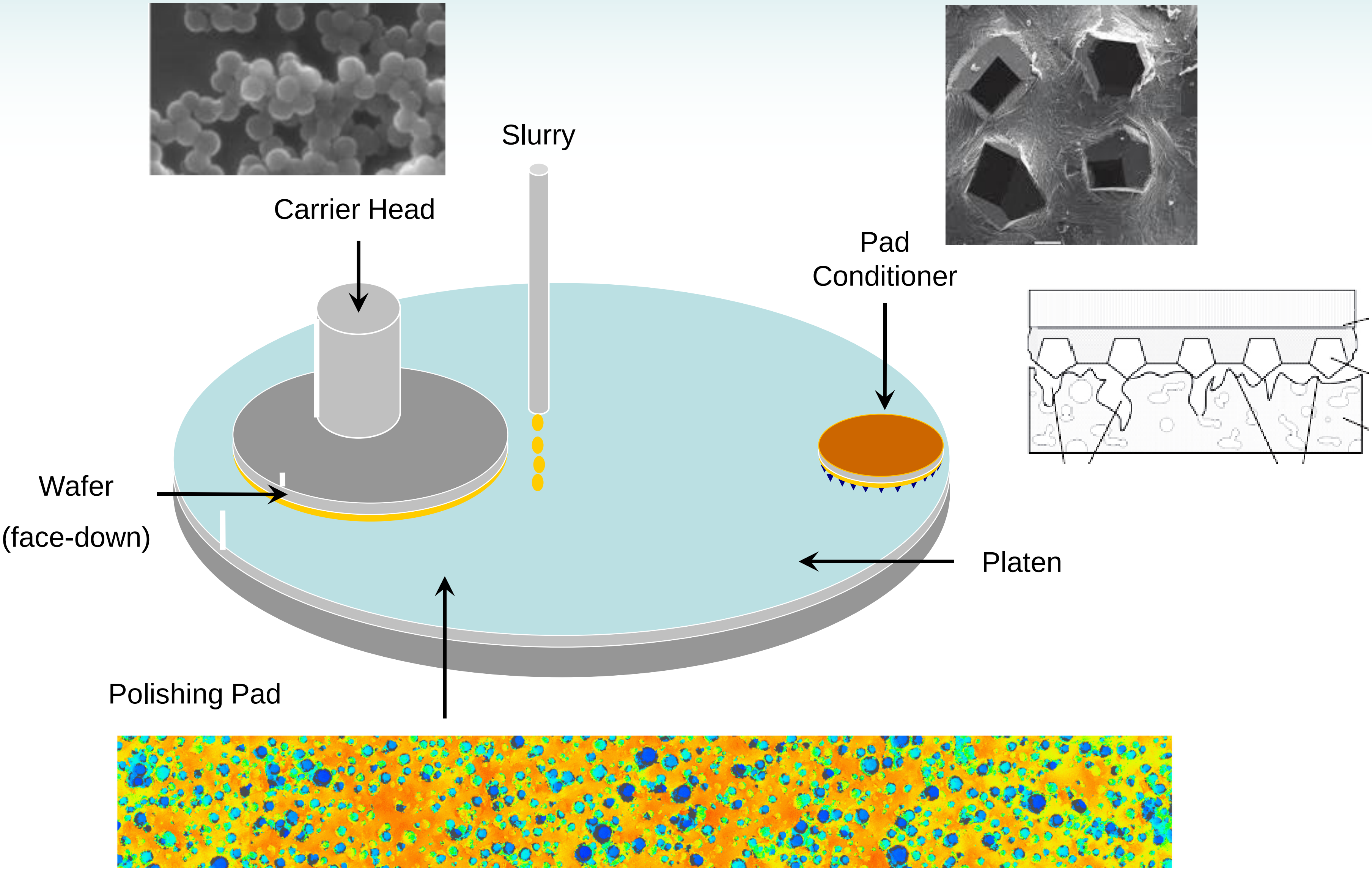
- CMP is a method and process used to achieve local (i.e., in the nm scale) and global (i.e., in the cm scale) surface planarity in IC devices through chemical and mechanical means.
- As such, it is (and will continue to be) a true technology enabler.



A 300-mm patterned wafer

10 to 100B Transistors

Chemical Mechanical Planarization



Slurry

Carrier Head

Pad Conditioner

Wafer

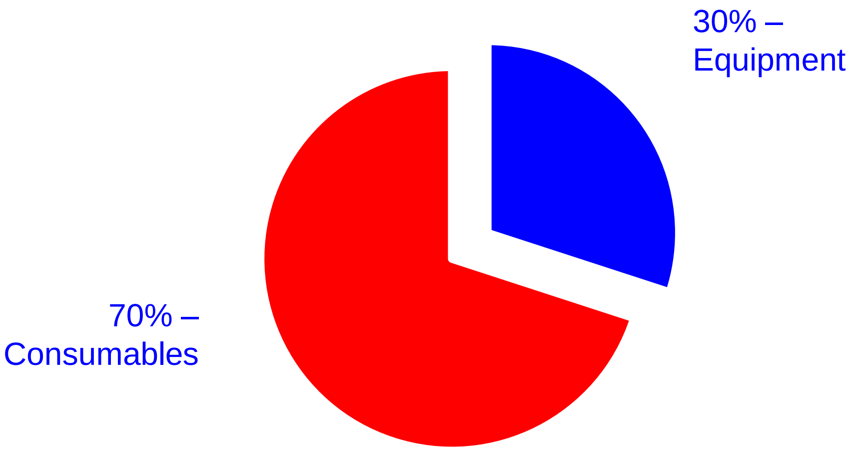
(face-down)

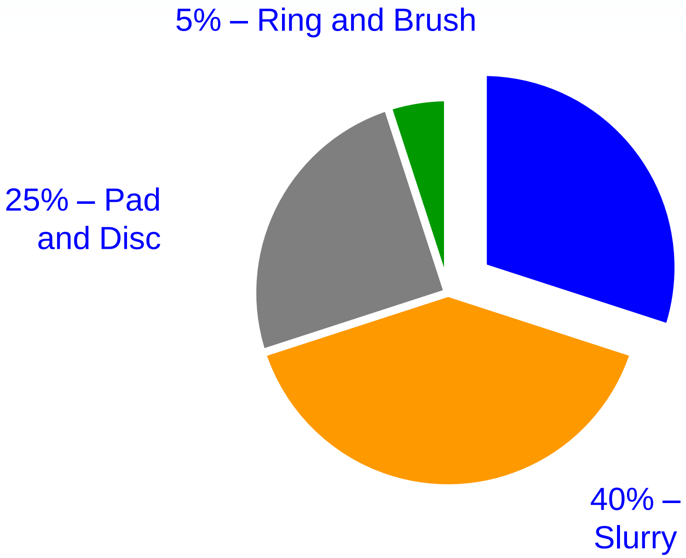
Platen

Polishing Pad

Problem Statement

- **In IC manufacturing, CMP is the 2nd most expensive process (after lithography).**

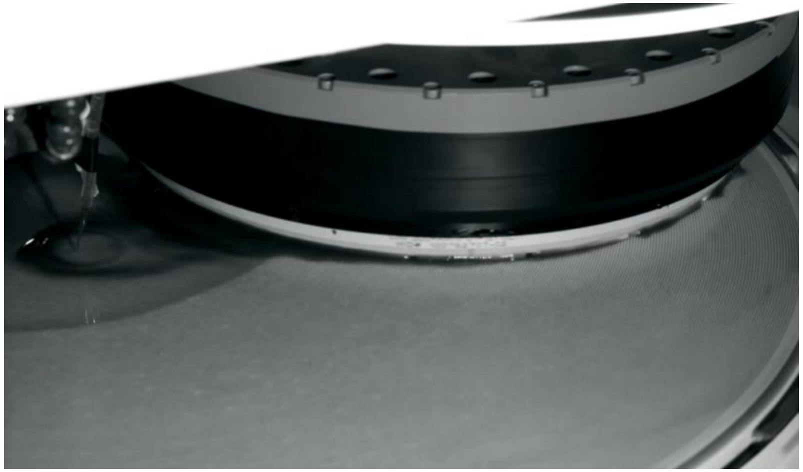




- **Pads and conditioning discs need to be changed after every 30 hours of use.**
- **Slurry contains high amounts of ultra-high purity colloidal silica or ceria nano-particles. It also contains chemical oxidizers, surfactants, chelating agents, pad fragments, organic acids, bases, bactericides and fungicides.**
- **Roughly 95 percent of the slurry is wasted during polishing.**

Problem Statement

- Large amounts of waste, when introduced into the environment, slurry will negatively and irreversibly affect myriad types of life and environmental cycles – Serious EHS concerns.
- Waste treatment adds another 5 percent to the COO.
- Recovery and reuse of spent CMP slurries has been investigated in the past, but no IC maker has viably reclaimed and recycled CMP slurries because:
  - ❖ Waste streams contain high amounts of rinse water – Diluted slurry is hard and expensive to recover.
  - ❖ Slurry makers keep their formulations secret – It is impossible for IC makers to reconstitute the slurry from the waste stream.
- Due to the extremely competitive landscape, IC makers must continuously increase yield and throughput, while embracing the need to reduce COO, stop large amounts of waste, and act and appear as good environmental citizens.



Our Vision re: Flucto-CMP®

- Today, the same HVM CMP tool must be able to planarize substrates by removing 2 to 2E7 nm of a single layer without compromising performance – 7 orders of magnitude difference!

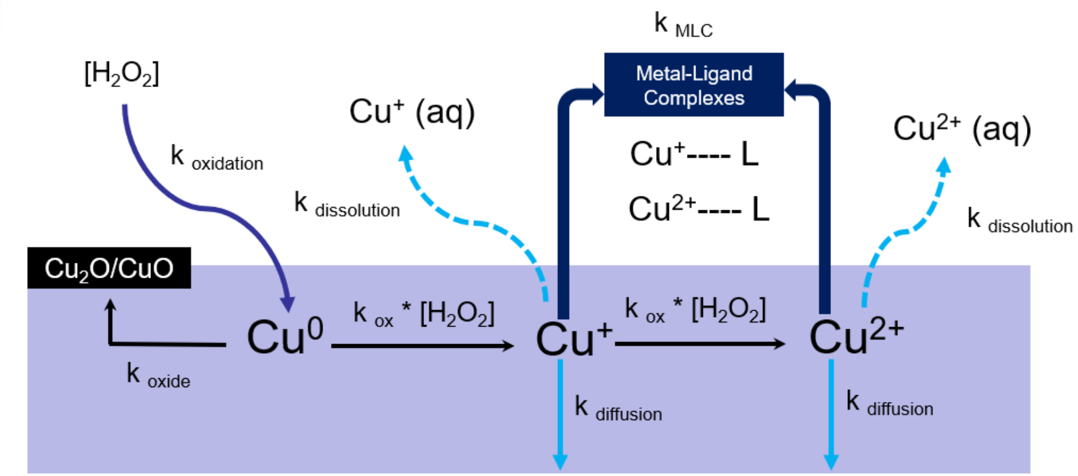
- In addition to platen temperature modulation, there are very few mechanical knobs (e.g., controls, hydraulics, pneumatics, kinematics and the like) that can be perfected in a polisher – Yet the chemical options are nearly infinite!

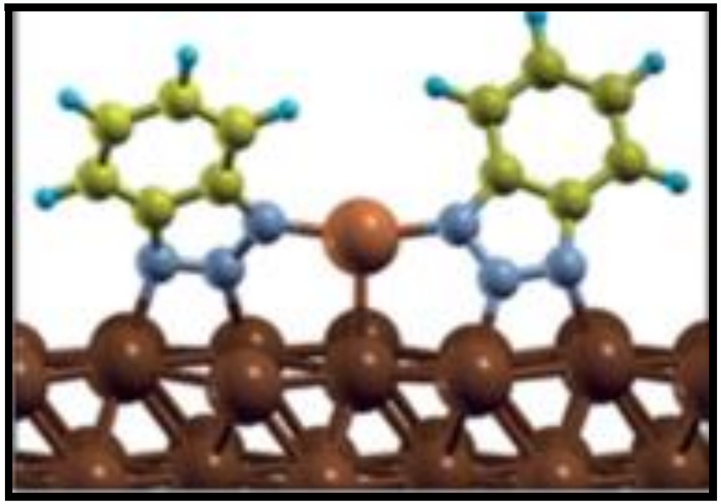
- For 2 years, we have been working to partially merge the polisher and slurry roadmaps via Flucto-CMP® where the combined slurry-polisher strengths complement each other to overcome their individual inherent weaknesses such as defects, gross vibrations, COO, slurry waste, RR, selectivity and WIWRRNU.

- IC makers wish to migrate to a slurry whereby its main properties (such as copper-to-barrier RR selectivity) can be toggled instantaneously and on-demand.

- Flucto means WAVE in Latin – We now provide on-demand off-the-shelf slurry activation using megasonic waves through a simple add-on to all HVM polishers.

BTA Modes of Inhibition in Conventional Copper CMP





Numerous studies of the interaction of BTA with copper reveal that the BTA molecule forms a coordination polymer above the surface featuring a Cu(I) center bridging between two BTA molecules.

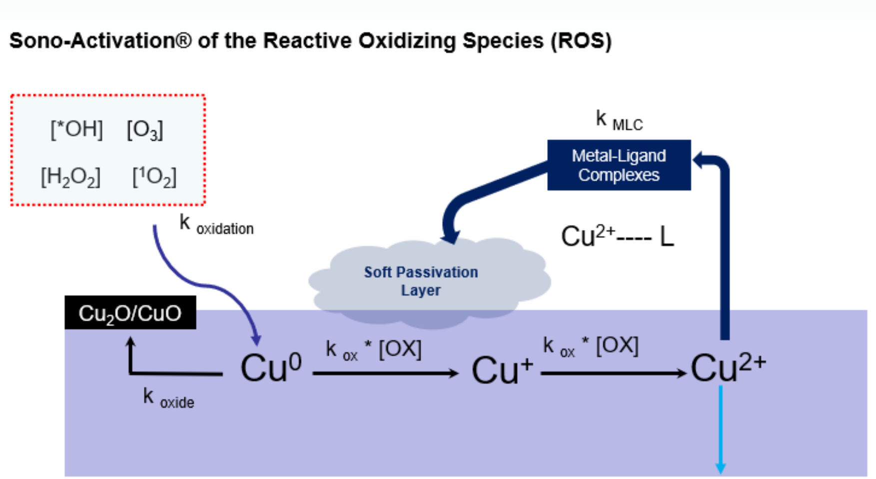
This polymerization leads to the formation of a DENSE and RUGGED passivation layer that causes large levels of vibration and requires significant mechanical action to remove at appreciable polish rates.

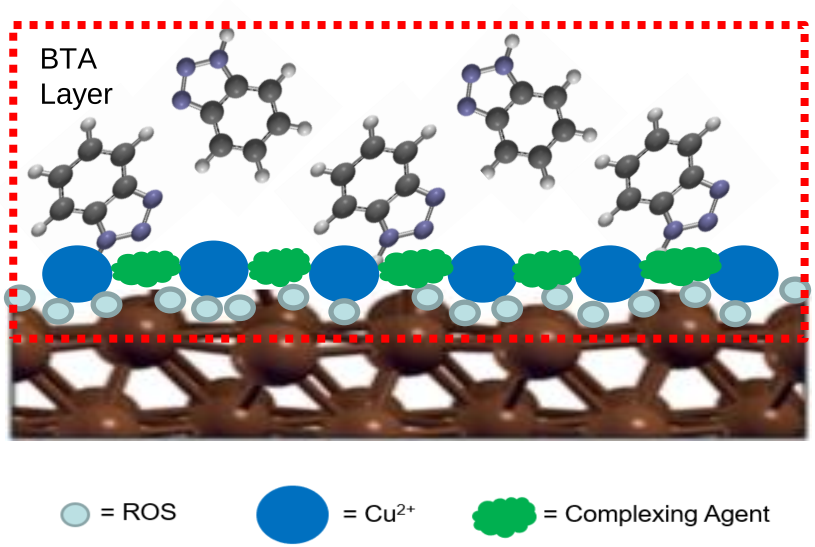
Non-Covalent Passivation Dynamics of Flucto-CMP®

- **In Flucto-CMP®, when it comes to material removal, it's all about one's ability to control the interface.**

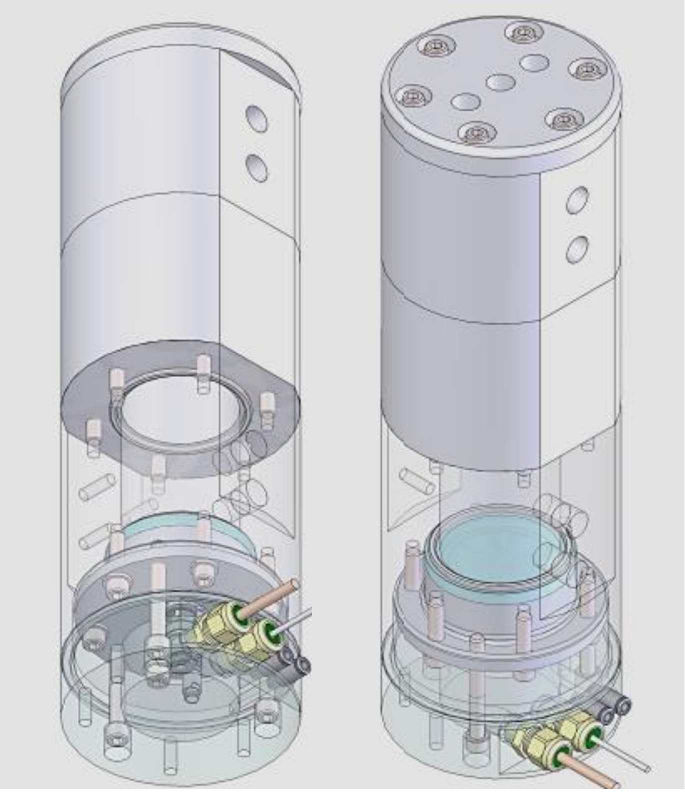
- **Enhanced CMP performance evolves from a balance of kinetic and thermodynamic processes. Modulation of these processes get activated by external stimuli such as sonication.**

- **The subsequent softer and less dense film formation dynamics results in effective material removal at less mechanically-aggressive conditions. This reduces vibration as well as wafer-level defects.**


Sono-Activation® of the Reactive Oxidizing Species (ROS)

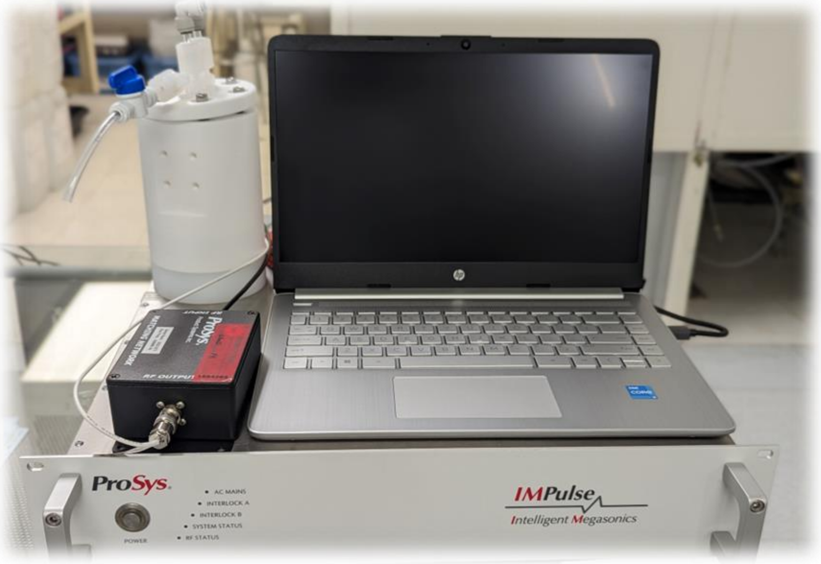


The Flucto-CMP® Setup



Flucto-CMP® Reactor with 1 MHz Transducer and a Maximum Power Density of 6 W/cm^2

Day-Tank Containing off-the-Shelf Cu, Ta or W Slurry with H2O2



RR with Flucto-CMP® on Blanket Substrates

- **100-mm wafers (including SiC):**
  - ✓ **Bulk Cu RR increase – 40% (Supplier A, C and D)**
  - ✓ **TSV Cu RR increase – 15% (Supplier A)**
  - ✓ **W RR increase – 25% (Supplier A and B)**
  - ✓ **Ta RR increase – 25% (Supplier A)**
  - ✓ **SiC RR increase – 100% (Araca slurry)**
- **300-mm wafers:**
  - ✓ **Bulk Cu RR increase – 15% (Supplier A)**
  - ✓ **W RR increase – 10% (Supplier A)**
  - ✓ **Great RTR repeatability →**
  - ✓ **DRACO RR increase – 35% (Supplier C)**
- **200-mm wafers:**
  - ✓ **Bulk Cu RR increase – 35% (Supplier A)**
  - ✓ **W RR increase – 15% (Supplier A)**
  - ✓ **Great RTR repeatability →**

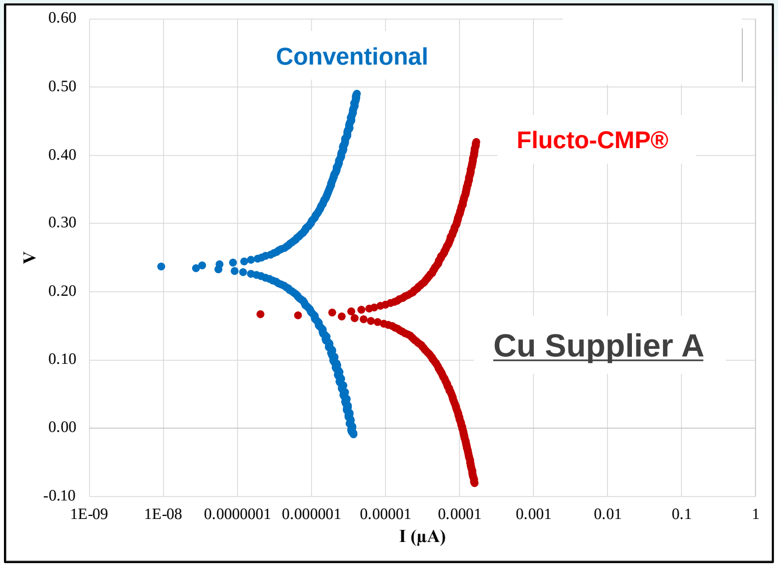
COPPER

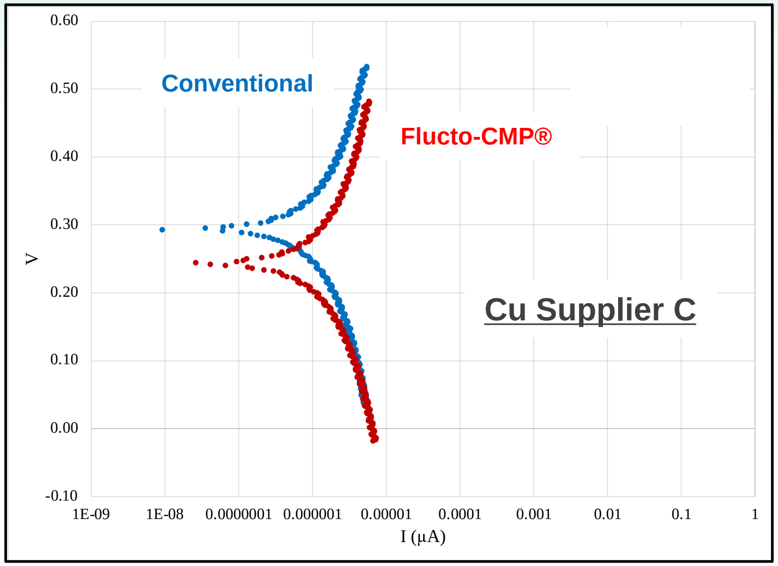
Run	Mean COF	Mean Pad Temp. (^{O}C)	Mean Removal Rate (A/min)
1	0.56	25.5	9190
2	0.532	25.8	8844
3	0.571	25.8	9025
4	0.543	25.7	8858
5	0.551	25.6	9175
6	0.562	26	9215
7	0.548	25.6	8957
8	0.542	25.7	9041
9	0.562	26.2	9038
10	0.554	26.2	8854
11	0.539	25.9	8958
12	0.565	25.5	9124
Average	0.552	25.8	9023
Standard Deviation (%)	2.2%	0.9%	1.5%

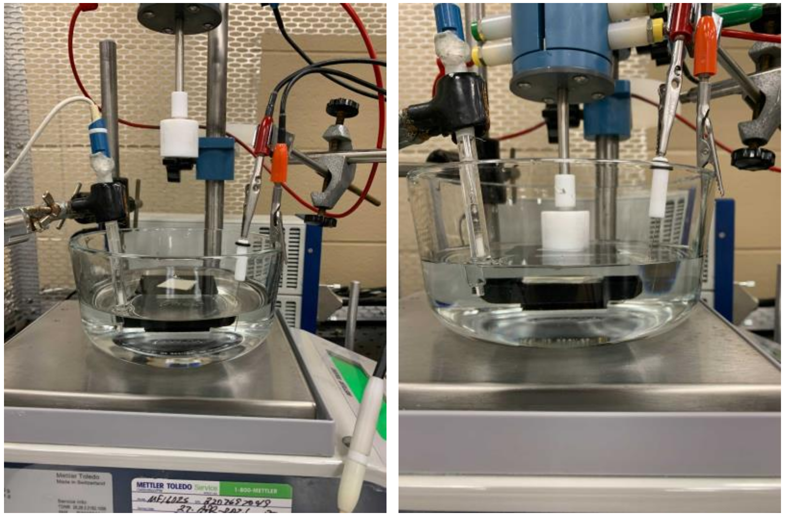
TUNGSTEN

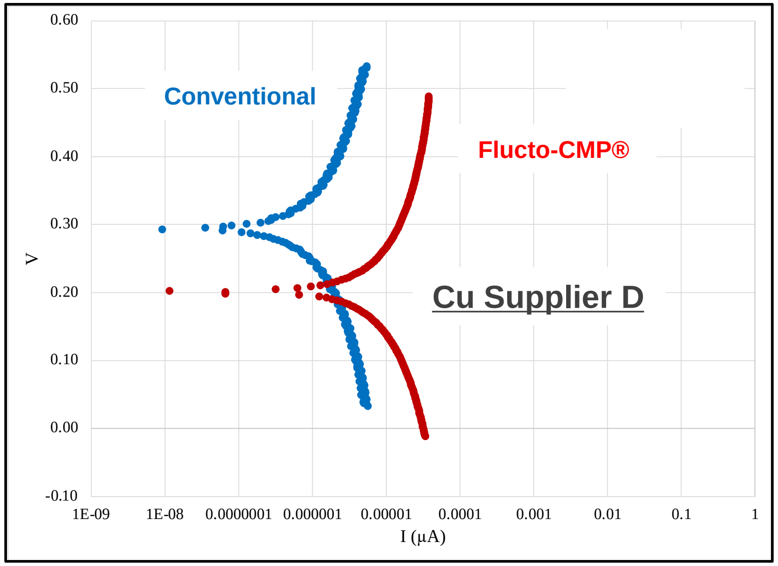
Run	Mean COF	Mean Pad Temp. (^{O}C)	Mean Removal Rate (A/min)
1	0.318	37.8	2435
2	0.299	37.2	2503
3	0.309	36.6	2453
4	0.308	36.9	2579
5	0.316	37.8	2471
6	0.301	36.9	2402
7	0.307	36.5	2475
8	0.294	37.1	2527
9	0.302	36.4	2481
10	0.294	36.9	2446
11	0.302	36.7	2490
12	0.301	37.6	2538
Average	0.304	37.0	2483
Standard Deviation (%)	2.5%	1.3%	2.0%

Electrochemical Analysis of Flucto-CMP®

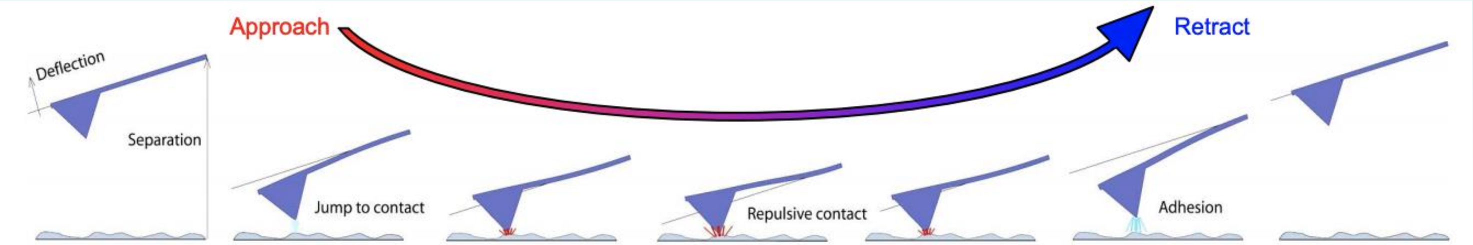


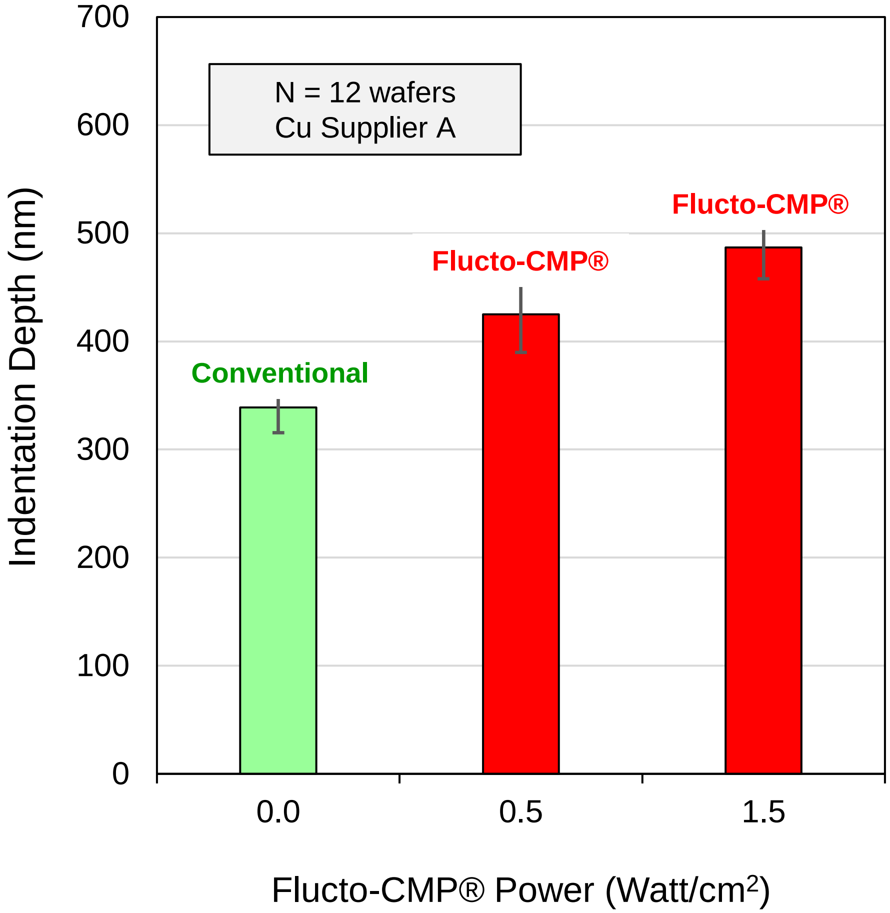


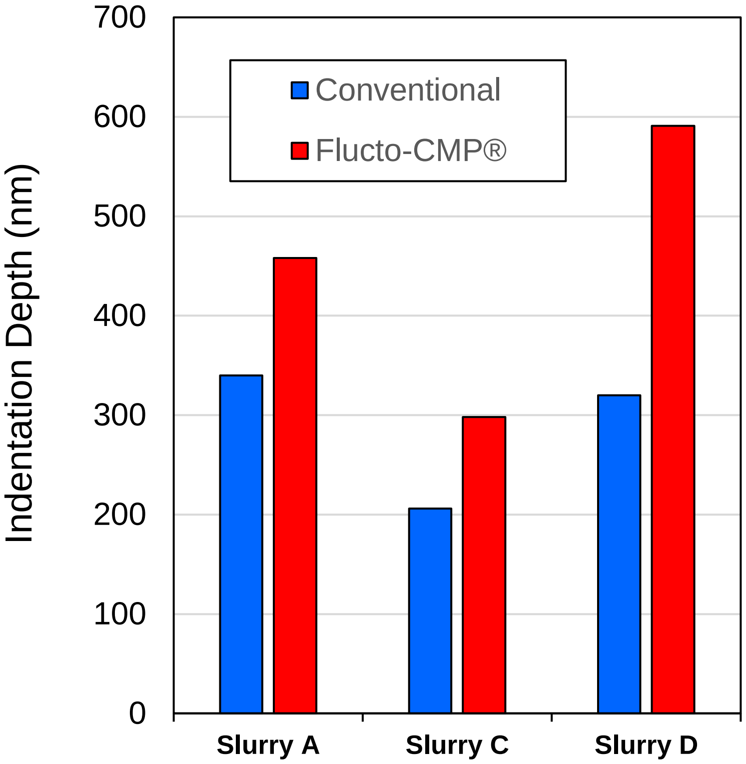




AFM Tip Indentation Depth of the Copper Passivation Layer

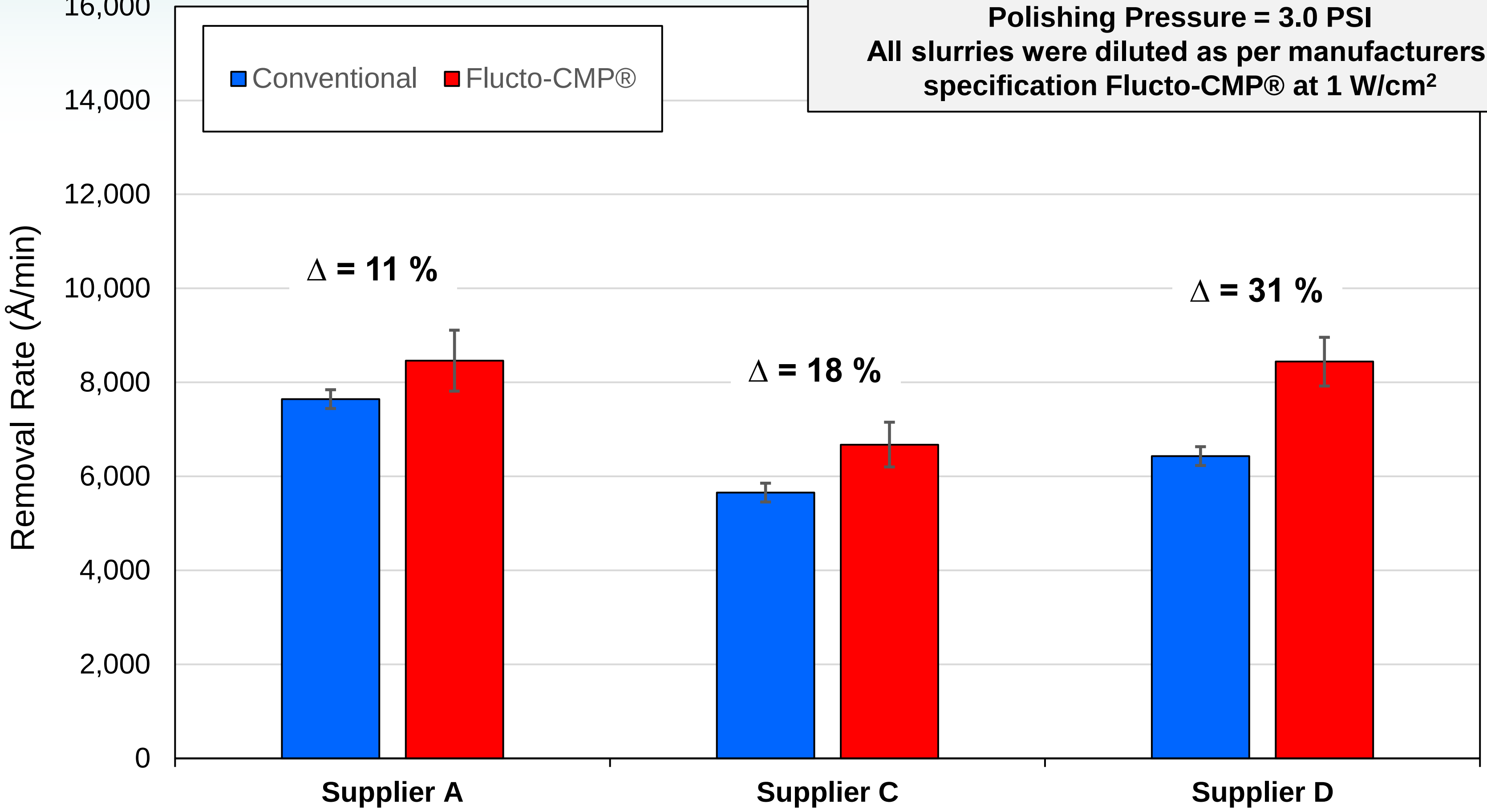






N = 12 wafers
All 3 slurries were diluted as per manufacturers' specification
Flucto-CMP® at 1 W/cm^2

Slurry Supplier Performance Comparison

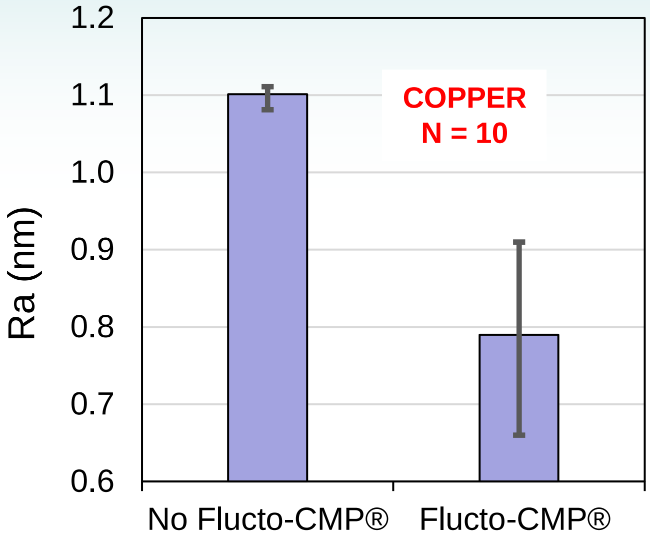


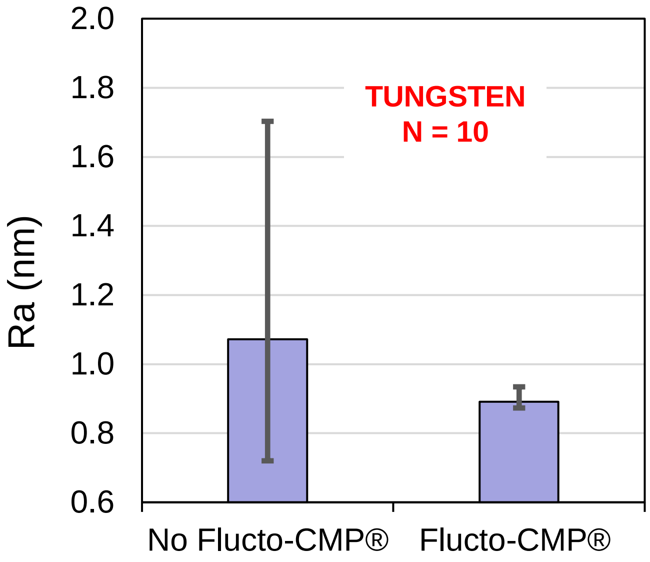
N = 8 wafers
Polishing Pressure = 3.0 PSI
All slurries were diluted as per manufacturers' specification Flucto-CMP® at 1 W/cm^2

REMEMBER – THE FASTER YOU POLISH, THE LESS SLURRY YOU USE AND THE LESS WASTE YOU HAVE TO DEAL WITH –
Flucto-CMP® CAN OFFER ATTRACTIVE ENVIRONMENTAL BENEFITS!

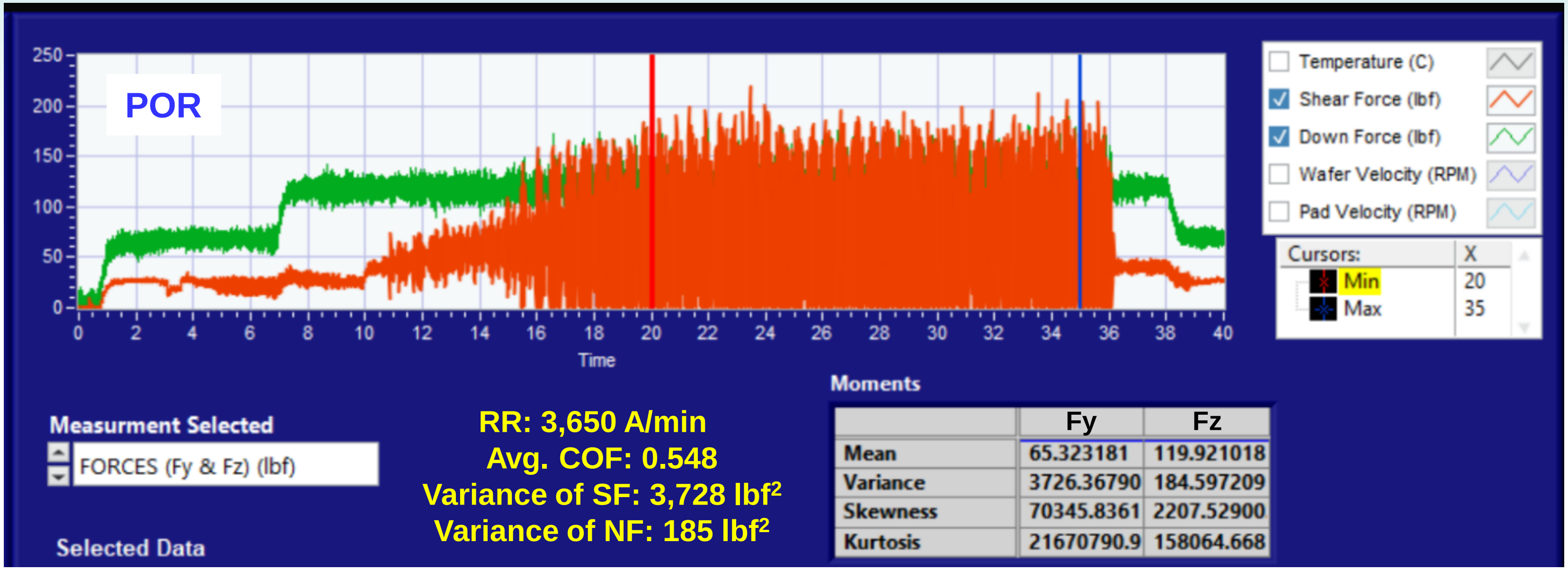
Our Rationale Regarding Defect Reduction

- We believe that defect reduction – one of the main attractions of our technology – is due to three separate effects as follows:
  - Sonic waves break up agglomerates. Already proven and patented by Samsung and Micron more than 20 years ago with ultrasonic radiation. The next 2 slides demonstrate the effectiveness of Flucto-CMP® on a modern-day copper slurry under megasonic waves.
  - Megasonic waves increase the concentration of the reactive oxidizing species and result in the formation of a softer passivation layer in which BTA and other molecules are non-covalently bonded on copper. This softer layer gets removed with greater ease compared to the dense covalently-bonded BTA-copper passivation layer in conventional CMP. Proven by AFM results on the penetration depth into the passivation layer under wet conditions. Dynamic electrochemical results also support our claim.
  - Lateral and normal vibrations of the carrier-wafer assembly are dramatically reduced (at times by as much as 80X) with Flucto-CMP® as supported by our real-time shear force and normal force variance results.





Time Traces – 1.5 PSI – 1.5 m/s – 1% H2O2



POR

- ☐ Temperature (C)
- ☑ Shear Force (lbf)
- ☑ Down Force (lbf)
- ☐ Wafer Velocity (RPM)
- ☐ Pad Velocity (RPM)

Cursors:	X
Min	20
Max	35

Measurment Selected

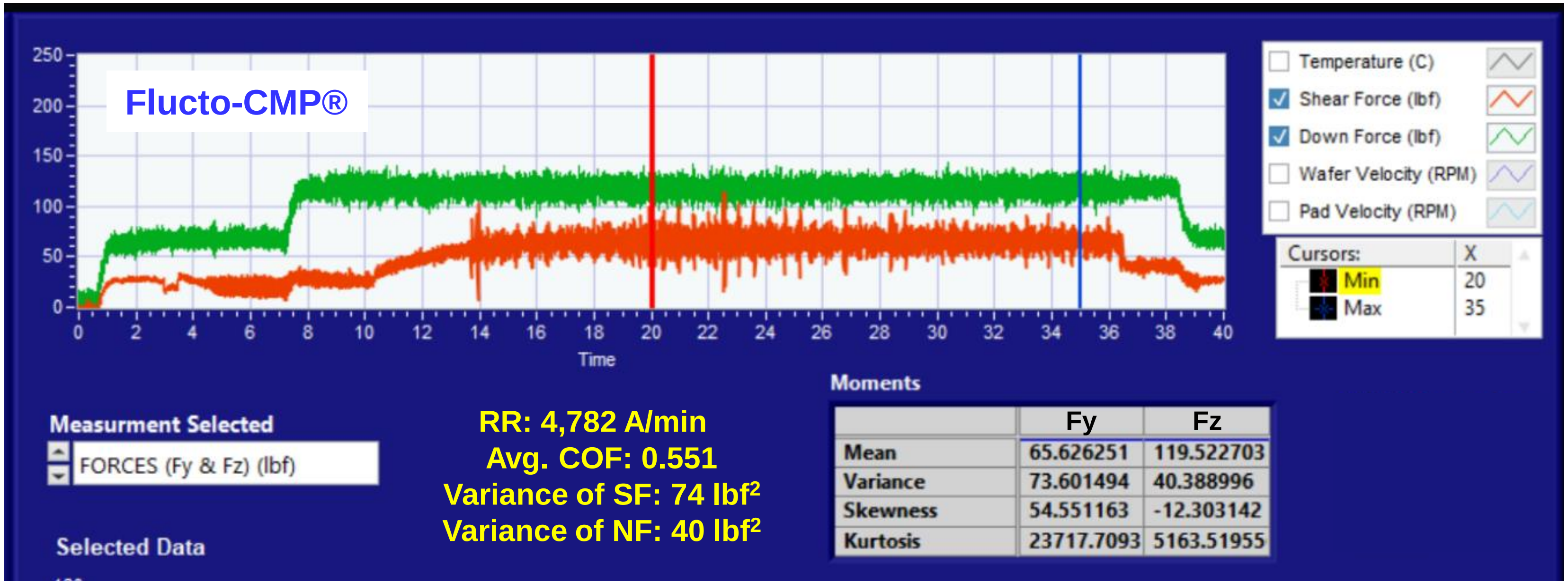
FORCES (Fy & Fz) (lbf)

Selected Data

RR: 3,650 A/min
Avg. COF: 0.548
Variance of SF: 3,728 lbf^2
Variance of NF: 185 lbf^2

Moments

	Fy	Fz
Mean	65.323181	119.921018
Variance	3726.36790	184.597209
Skewness	70345.8361	2207.52900
Kurtosis	21670790.9	158064.668



Flucto-CMP®

- ☐ Temperature (C)
- ☑ Shear Force (lbf)
- ☑ Down Force (lbf)
- ☐ Wafer Velocity (RPM)
- ☐ Pad Velocity (RPM)

Cursors:	X
Min	20
Max	35

Measurment Selected

FORCES (Fy & Fz) (lbf)

Selected Data

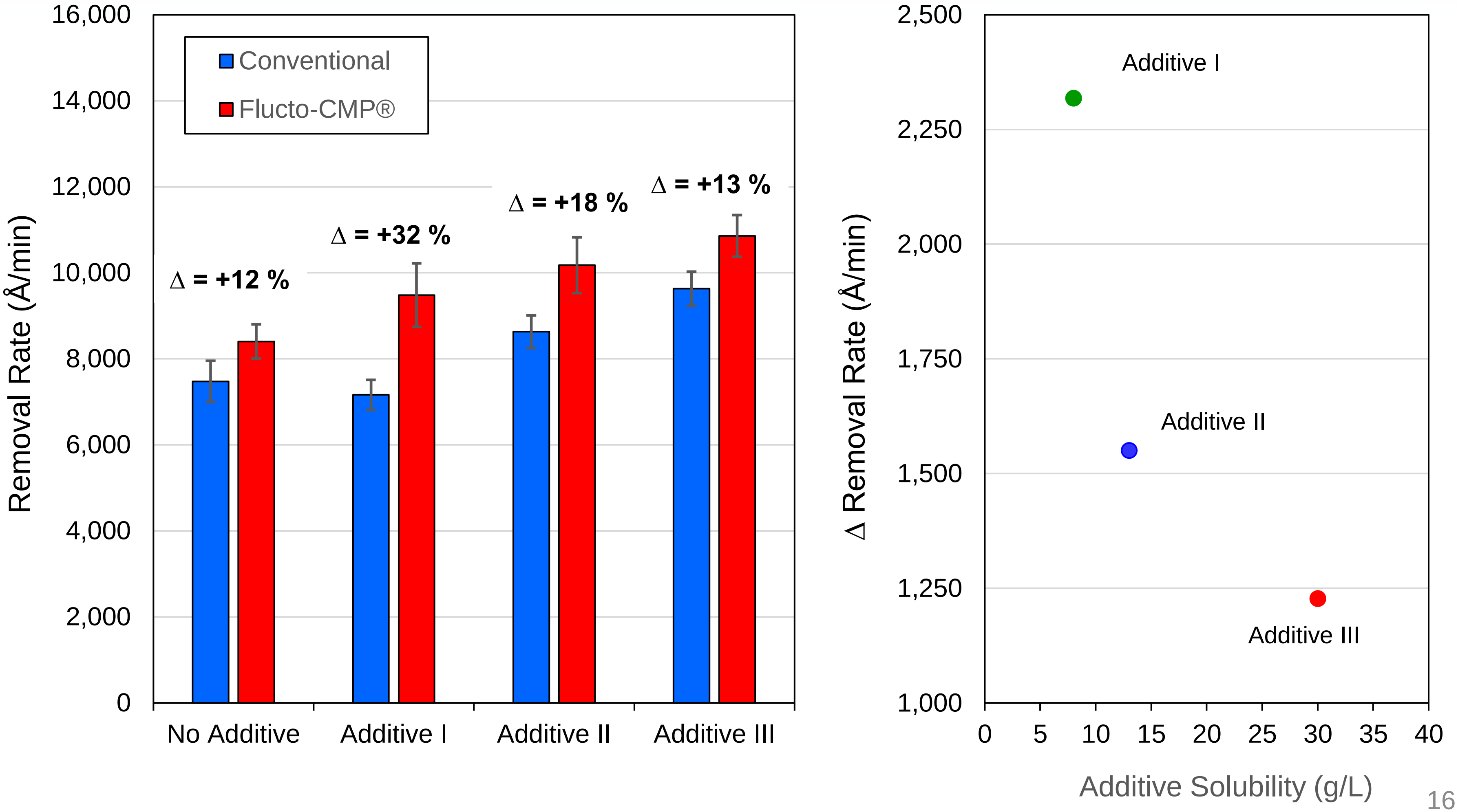
RR: 4,782 A/min
Avg. COF: 0.551
Variance of SF: 74 lbf^2
Variance of NF: 40 lbf^2

Moments

	Fy	Fz
Mean	65.626251	119.522703
Variance	73.601494	40.388996
Skewness	54.551163	-12.303142
Kurtosis	23717.7093	5163.51955

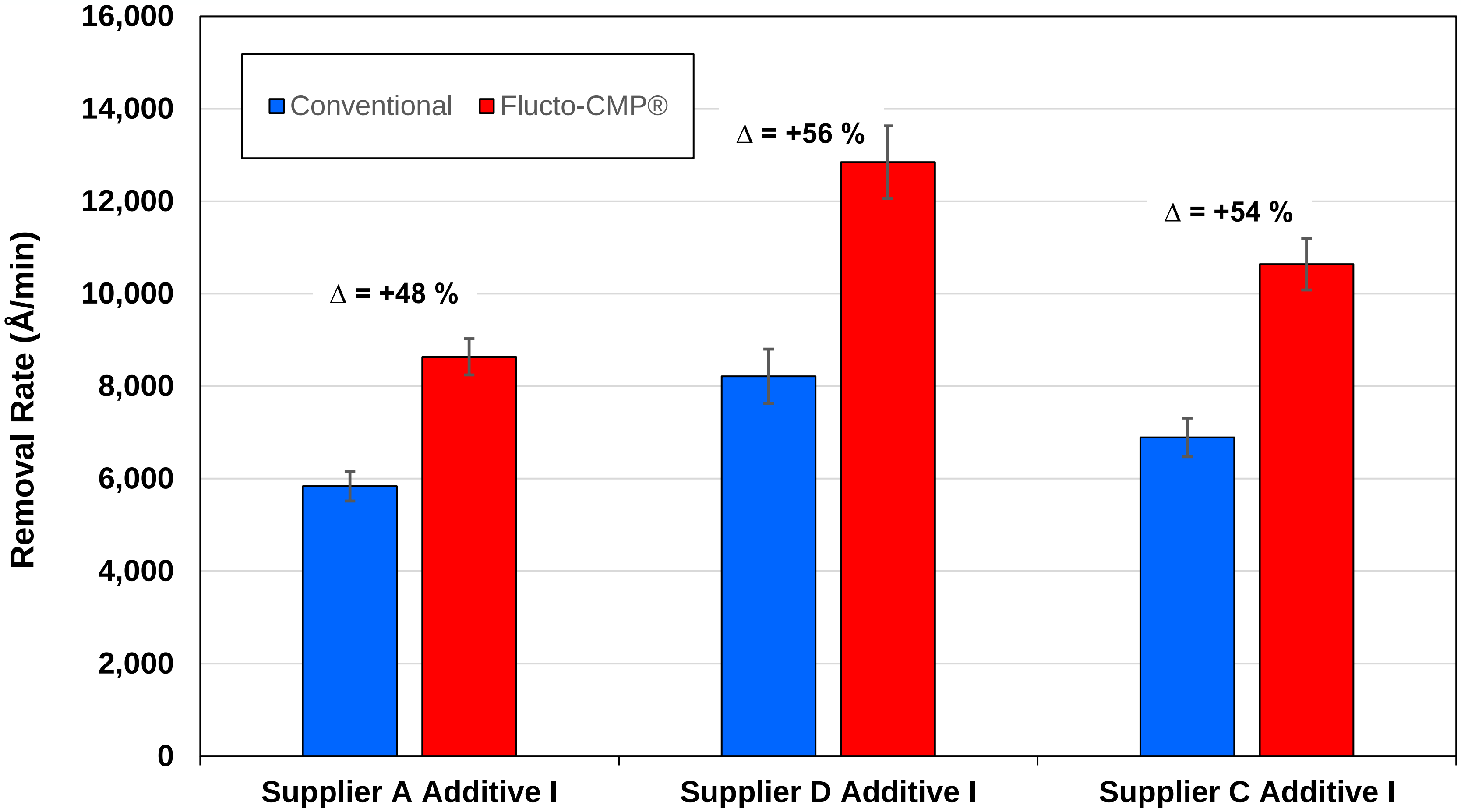
Addition of Sono-Activated® Additives to Cu Supplier A Slurry

N = 8 wafers
Polishing Pressure= 3.0 PSI
Cu Supplier A
Flucto-CMP® at 1 W/cm²

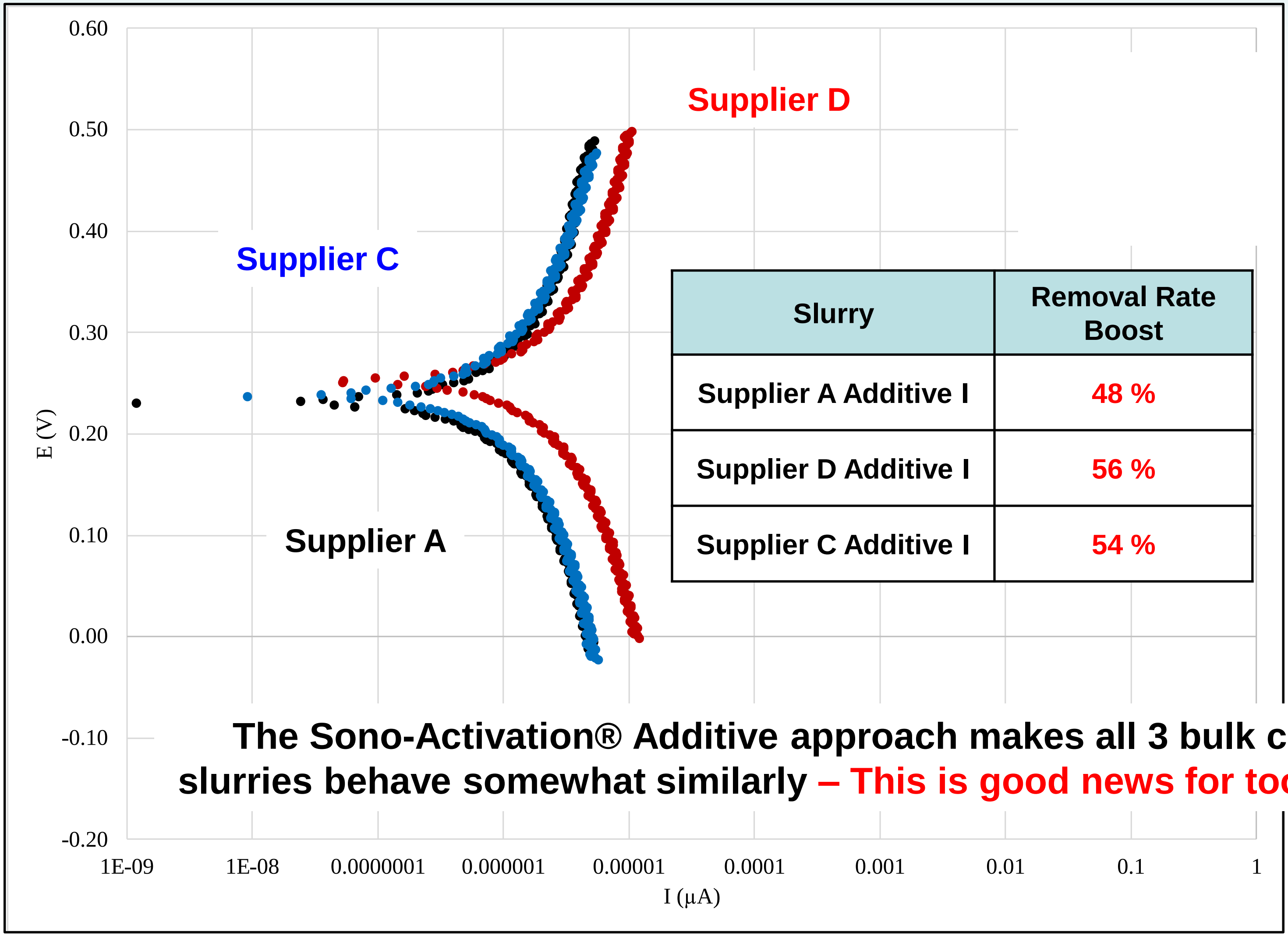


Effect of Sono-Activated® Additive on 3 Slurries

N = 8 wafers
Polishing Pressure = 3.0 PSI
All slurries were diluted as per manufacturer's specification
Flucto-CMP® at 1 W/cm^2



Film Formation Kinetics with Sono-Activated® Additive Approach



Slurry	Removal Rate Boost
Supplier A Additive I	48 %
Supplier D Additive I	56 %
Supplier C Additive I	54 %

The Sono-Activation® Additive approach makes all 3 bulk copper slurries behave somewhat similarly – This is good news for toolmakers!

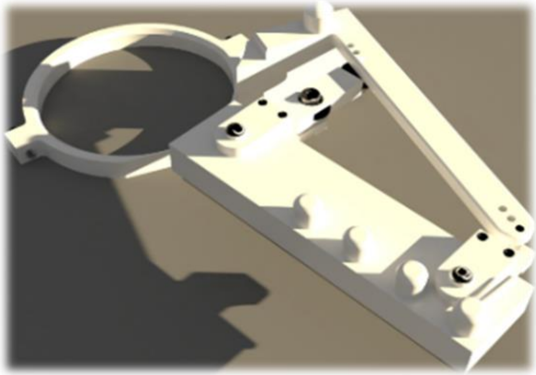
Our Vision re: Slurry Injection System (SIS®)

- Slurries are expensive and reducing their flow rate, and the number of wafer-level defects that they cause, are among the top objectives of any CMP module leader and fab manager. This is especially true for older fabs as reducing op-ex id the main concern!

- Slurries vary in chemical and physical properties and they rely on different mechanisms for removal. A simple reduction in flow without understanding the nature of the slurry, and without fundamentally changing the method of slurry dispense, can cause adverse effects such as:

  - Unfavorable flow patterns on the pad.
  - Lower RR, higher WIWRRNU and higher wafer-level defects.
  - Slower displacement of rinse water from the pad surface.

- Each IC fab employs different processes and consumables. A universal technological solution does not exists for flow rate and defect reduction.



SIS® Principle of Operation

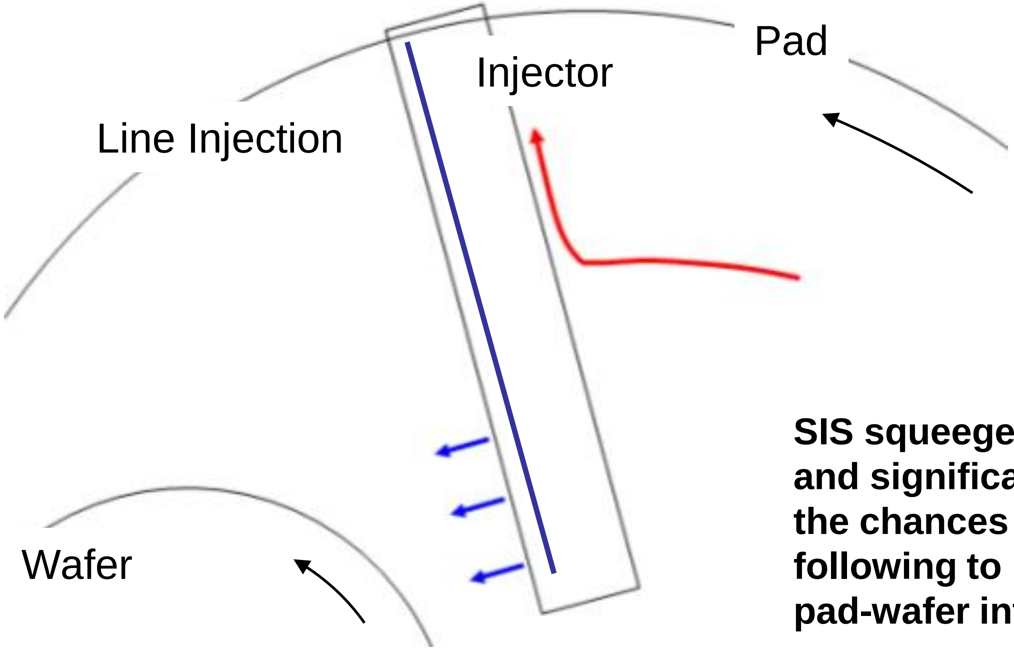
Injector bottom is made of PEEK or PPS. It contacts the pad.

With the SIS, the air interface is eliminated.

Fresh slurry is applied between the injector bottom and the pad which results in a thinner fluid layer and less micro-hydrodynamic lubrication.

SIS can be configured to inject at multiple points to accommodate pad grooving differences.

SIS is flexible. It conforms to the pad and its macro-texture as the pad wears over time due to abrasion by the conditioner and the retaining ring.

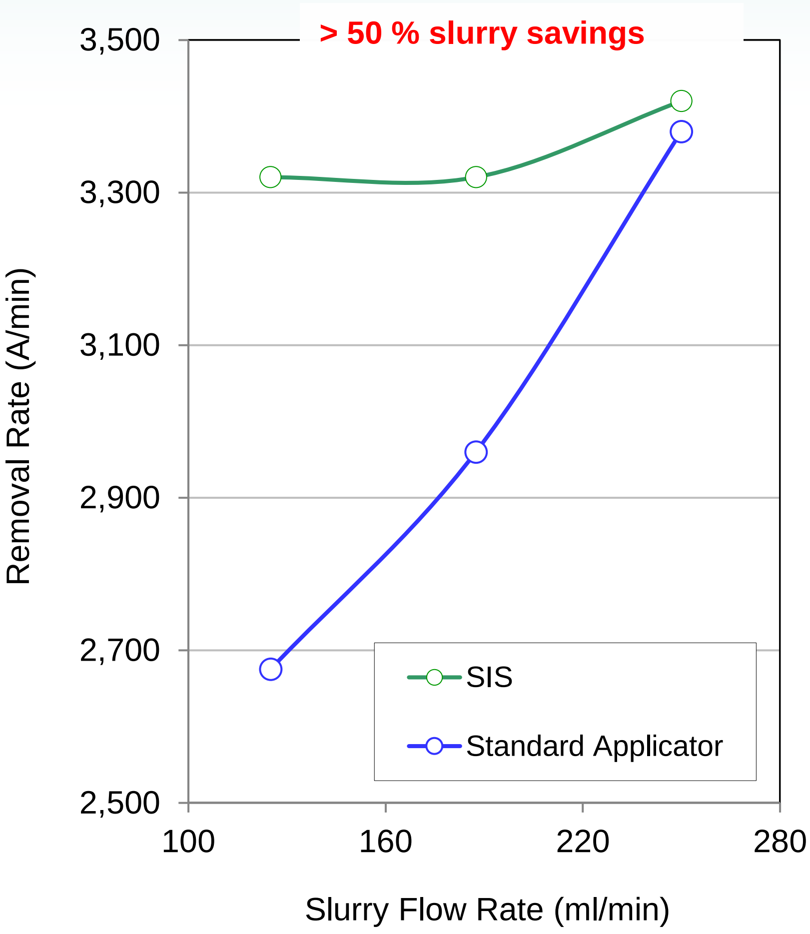


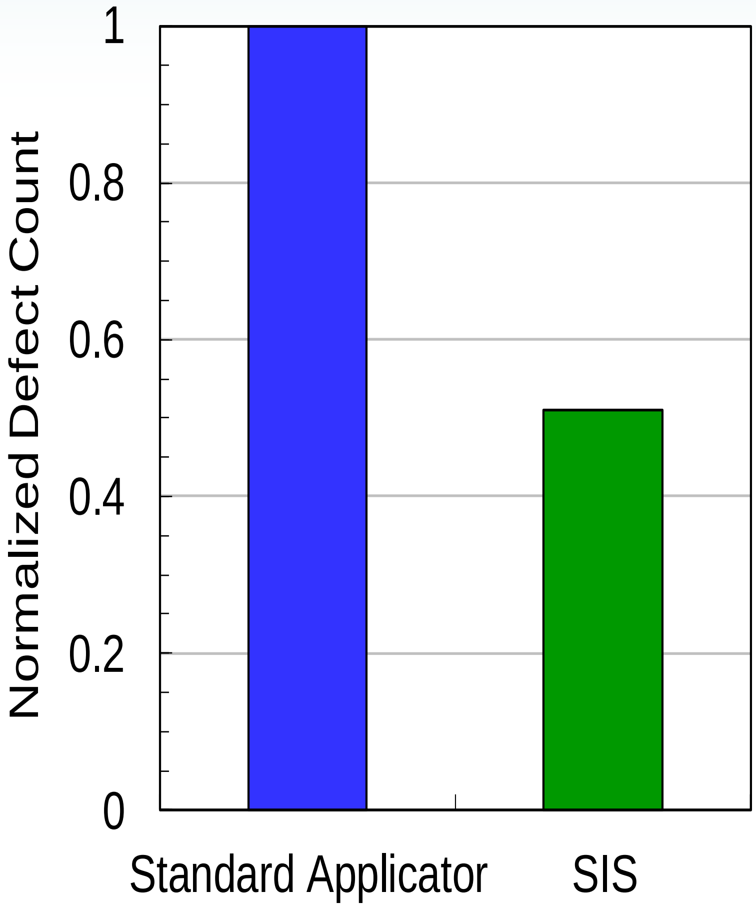
Multi-Point Injection

SIS squeegees the pad and significantly reduces the chances of the following to re-enter the pad-wafer interface:

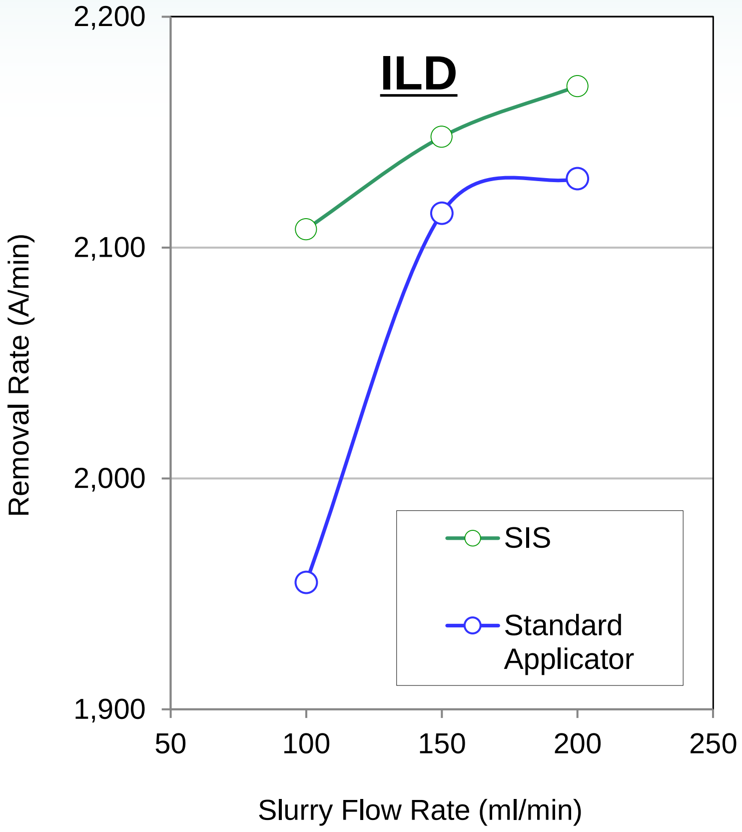
- Pad rinse water
- Used slurry
- Reaction products
- Foam
- Pad debris and particles

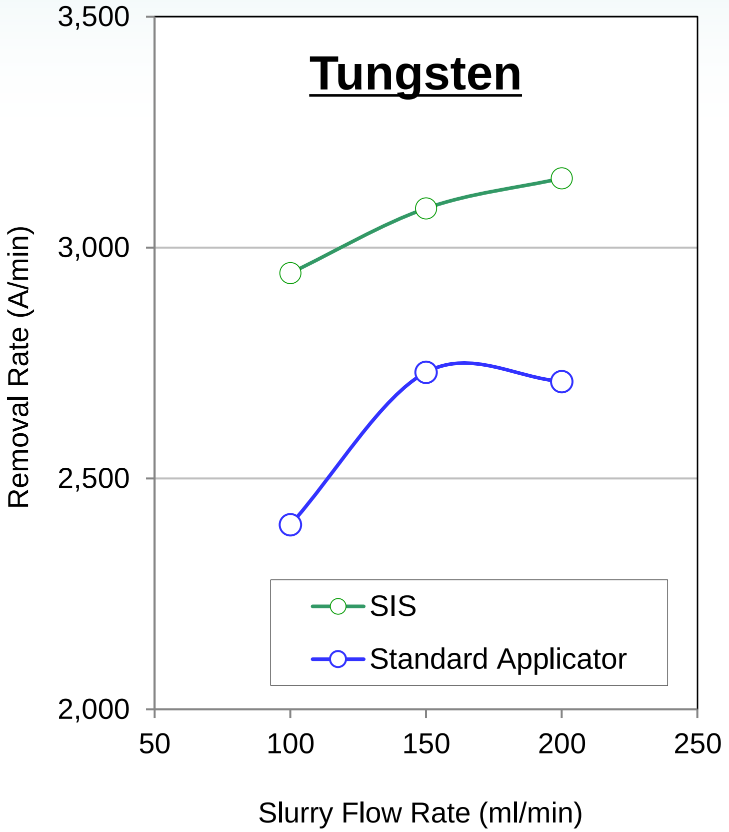
SIS Results – 300-mm HVM Fab No. 1 – TUNGSTEN


> 50 % slurry savings



SIS Results – 300-mm HVM Fab No. 2



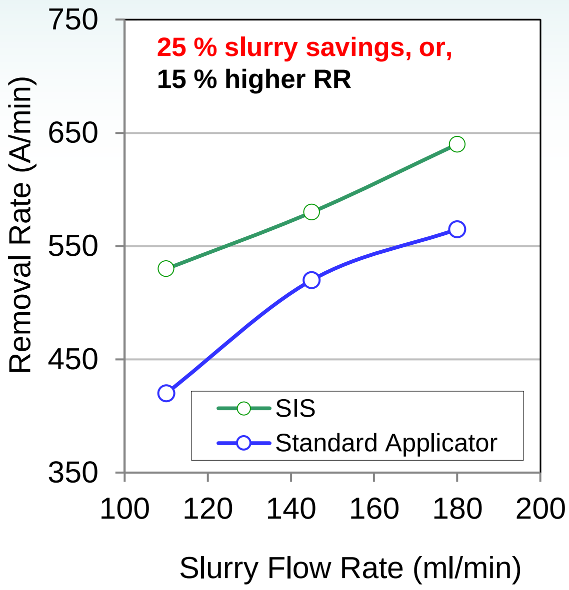


35 % slurry savings, or,
3 % higher RR
30 percent drop in wafer-level defects during ILD CMP

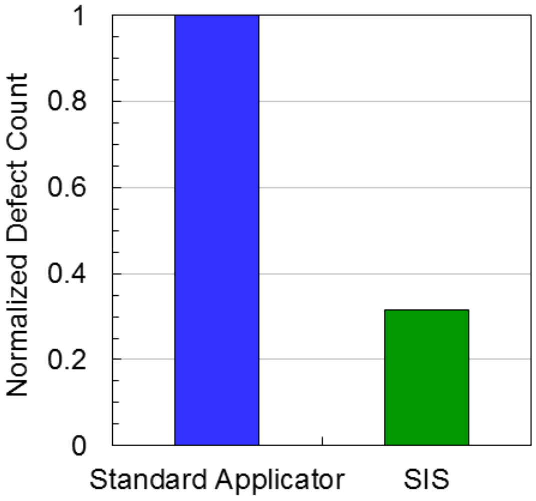
> 50 % slurry savings, or,
16 % higher RR
2X lower wafer-level defects during W CMP

SIS Results – 300-mm HVM Fab No. 3

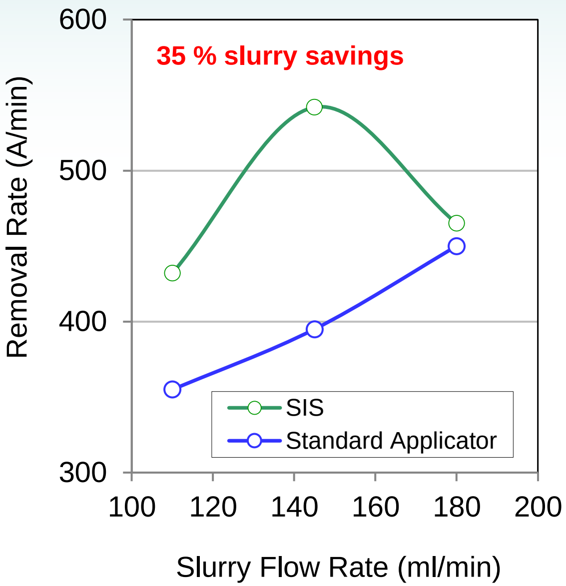
Barrier



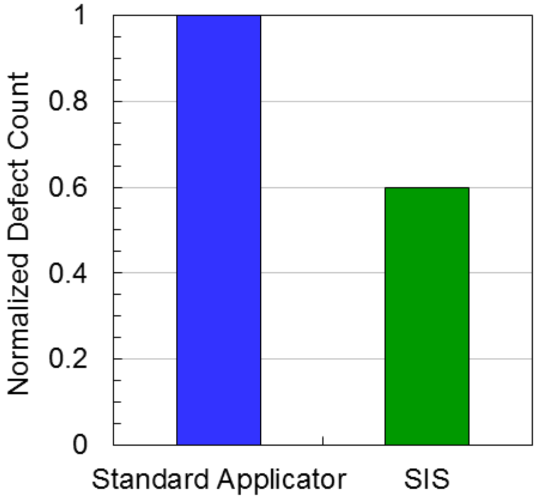
25 % slurry savings, or,
15 % higher RR



Copper



35 % slurry savings



General Summary

- **CMP continues to be one of the most Environmentally-UNFRIENDLY processes in IC manufacturing.**
- **We showed that Flucto-CMP® and SIS® can each reduce polish times by at least 30 percent. When combined, about 50 percent savings in slurry! This means that the industry will also end up using at least 30 percent less pads and conditioning discs.**
- **Pads are made of polyurethane, taking more than 150 years to biodegrade, so a 30 percent reduction in their use translates to not having to discard 2MM kilograms of solid polyurethane each year.**
- **Each conditioning disc contains up to 30,000 synthetic diamonds with only about 100 of them doing the job of actively rejuvenating the pad surface. Diamonds require massive amounts of electricity to be manufactured (Temperature = 1,700 degrees Celsius, and Pressure = 70,000 ATMs). We can reduce this by 30 to 50 percent.**
- **A 30 – 50 percent reduction in waste, and the energy for making slurries, pads and diamond discs is quite significant in light of the industry's long-term environmental, health and safety goals. SIS ® and Flucto-CMP® can certainly do that.**
- **Most importantly, SIS® and Flucto-CMP® result in higher yields at IC fabs. This, in and of itself, results in the most environmentally-friendly outcome!**