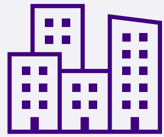
Characterization and Metrology Development of a Copper Plating Bath for Hybrid Bonding Interconnect

Mike Pavlov, Artyom Duev, Danni Lin, Eugene Shalyt, Cynthia Wang and William Schultz

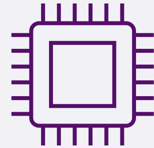
21st International Conference on Device Packaging

March 5, 2025

KLA at a Glance



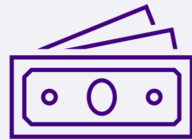
Founded in
1976



Headquarters in
Milpitas, CA

18
Regions

~15,000
Employees

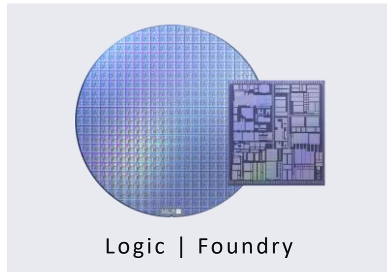


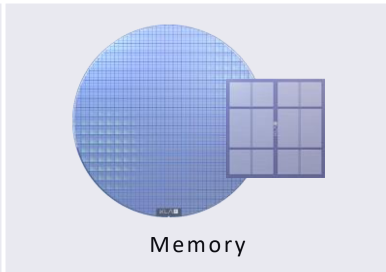
10.85B
CY2024 Revenue

>65%
PhD/Master's among professional roles

KLA's Role in the Electronics Ecosystem

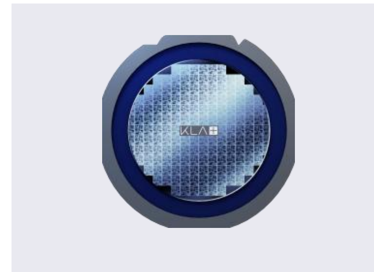
CHIPS


Logic | Foundry

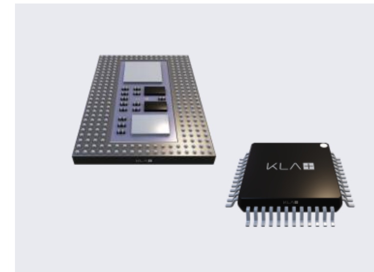

Memory

Specialty | Legacy

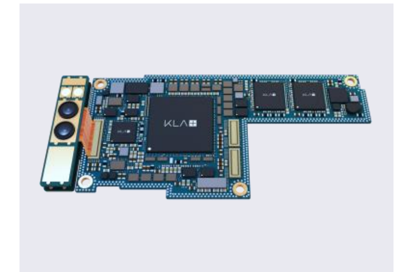
WAFER-LEVEL PACKAGING



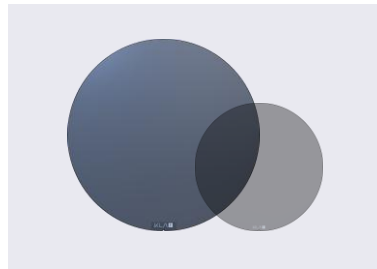
COMPONENTS



PRINTED CIRCUIT BOARDS



WAFERS



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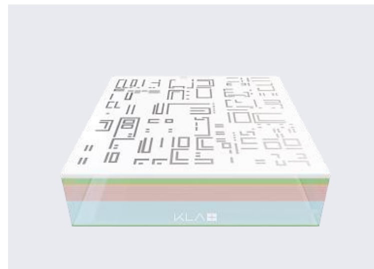
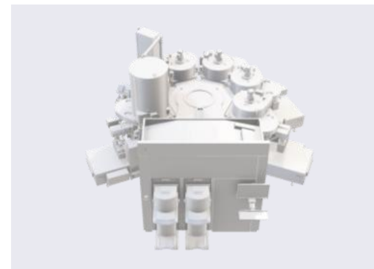
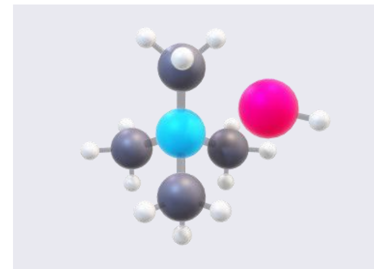


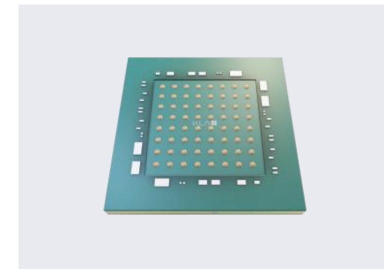
SEMI OEMs



CHEMICALS | MATERIALS



IC SUBSTRATES



END MARKETS

Data Center

Artificial Intelligence

5G Infrastructure

Mobile

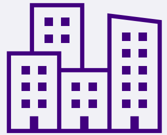
Automotive

PC / Tablet

Metaverse (AR/VR)

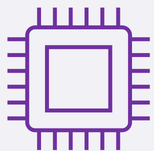
KLA

KLA's Chemistry Process Control Business



- Providing chemistry process control solutions since 1987

- Chemistry business located in Totowa, NJ, USA



Leadership in Chemical Metrology

Semi			Advanced Packaging (AP) & PCB	
BEOL Damascene		Wet Cleans	Plating in Advanced Packaging	
Quali-Line® Prima® (Cu)	Quali-Line Quanta® (Co)	QualiSurf® Series	Quali-Fill® Libra®	Quali-Dose®

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Outline

- Packaging Roadmap
- Hybrid Bonding Interconnect
- Electroplating Copper Baths for Hybrid Bonding Applications
- Analytical Considerations
- Bath Components Effects
- Analytical Methods and Analysis Results
- Conclusions

Semiconductor Packaging Roadmap

Combined Timeline of 3D Interconnect Density and Technology Node

YOLE Intelligence

3D Interconnect Density (mm-3) Log Scale

1,E+13
1,E+12
1,E+11
1,E+10
1,E+09
1,E+08
1,E+07
1,E+06
1,E+05
1,E+04
1,E+03
1,E+02
1,E+01
1,E+00

FE Technology Node (µm)

TSMC: SoIC in CoWoS
TSMC: SoIC in InFO
SOURCE: TSMC
3D ID **with** 3D/2.5D Packaging
Hybrid Bonding
TSMC: InFO_oS
ASE: FOCoS
TSMC: CoWoS
Intel: Foveros
Intel: EMIB
TSMC: LSI
Si Bridge
IC Substrate
PCB
Die
HBM
DRAM
3D ID **without** 3D/2.5D Packaging
UHD FO | 2.5D Si Interposers | Embedded Die
FC CSP/BGA
Fan-In WLP
Flip-Chip | WLCSP

10,0µm
3,0µm
1,0µm
0,350µm 0,090µm
0,028µm
0,007µm
0,003µm

1970 1975 1978 1980 1985 1990 1995 2000 2005 2010 2015 2020 2025 2030 2035 2040 2045 2050

Timeline

3D ID = (No. of lines per mm) * (No. of vertical interconnects per mm²)

3D Interconnect Density Data adopted from TSMC
Technology Node here refers to front-end node and is based on the expected average value within the industry.

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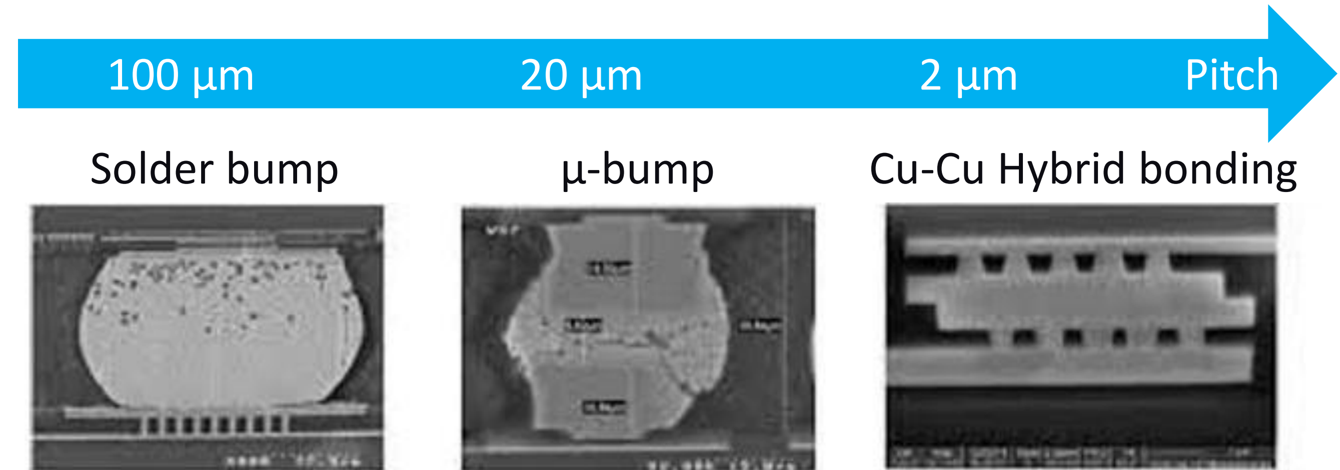
Why Hybrid Bonding?

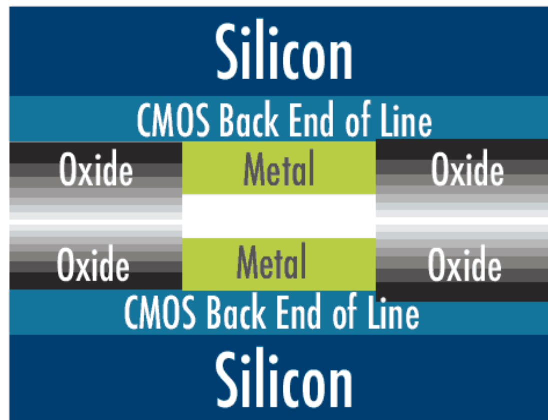
- Allows advanced 3D device stacking
- Highest I/O
- Enables sub-10-µm bonding pitch
- Higher memory density
- Expanded bandwidth
- Increased power
- Improved speed efficiency
- Eliminates the need for bumps, improving performance with no power and signal penalties



Hybrid Bonding Basics*

Fundamentals

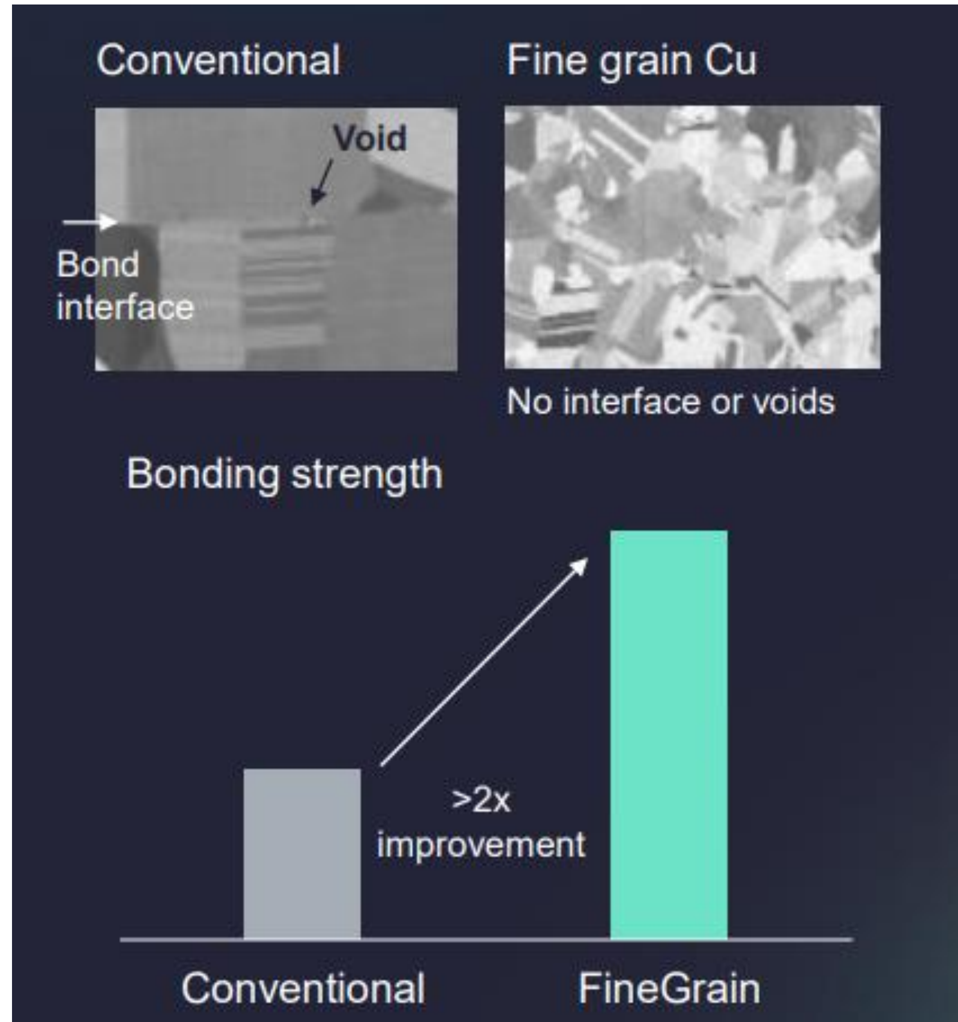
- Hybrid bonding is a permanent bond that combines a dielectric bond (SiOx) with embedded metal (Cu) to form interconnections. It's become known industry-wide as direct bond interconnect (DBI). Hybrid bonding extends fusion bonding with embedded metal pads in the bond interface, which allows face-to-face connection of the wafers.



* Manufacturing, Packaging & Materials, "Hybrid Bonding Basics: What Is Hybrid Bonding?", August 18, 2022, By Jessica Albright

Enabling Advanced Packaging

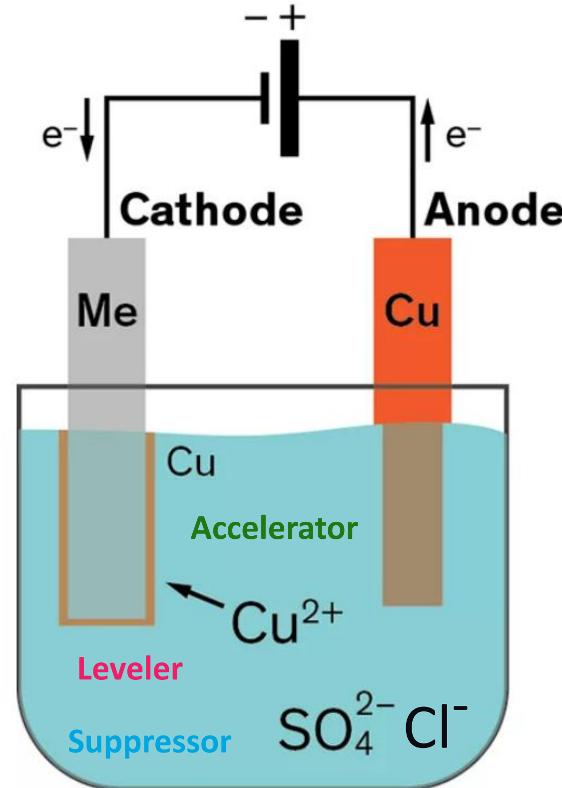
Grain Engineering



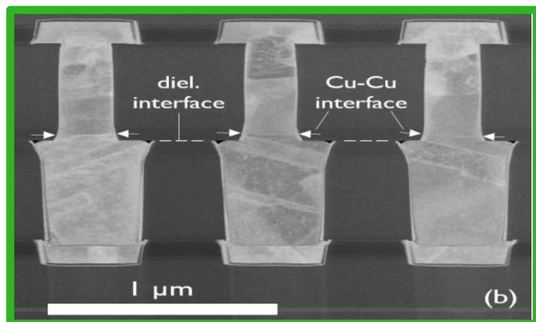
Copper Electrodeposition from modified bath

Source: Lam Research Investor Day, Feb 2025.

Plating Tools and Plating Chemistries for Copper Deposition



Plating Tool in closed loop with CMS

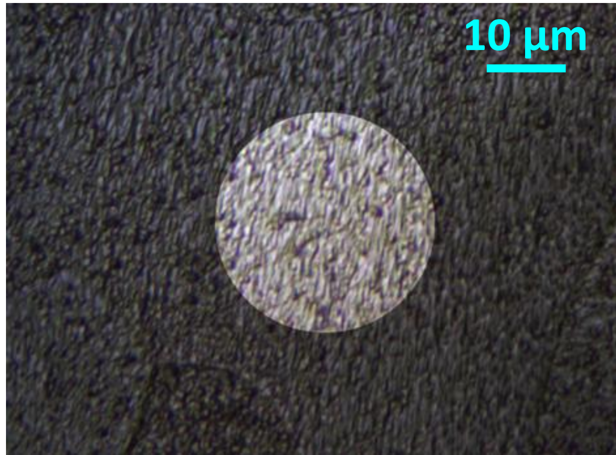
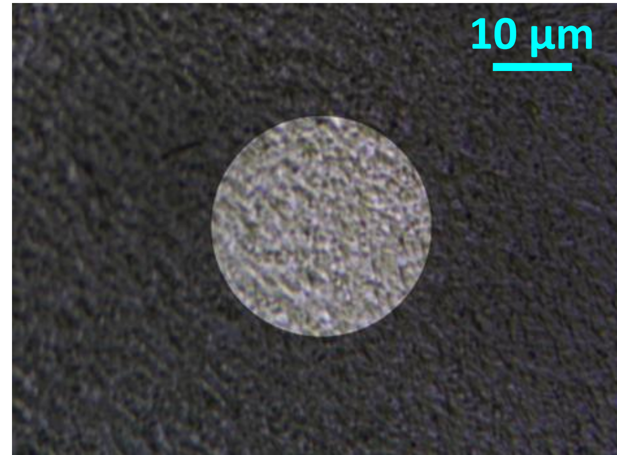
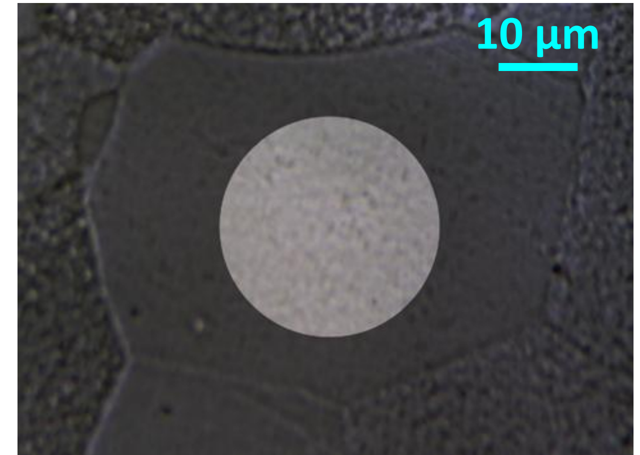
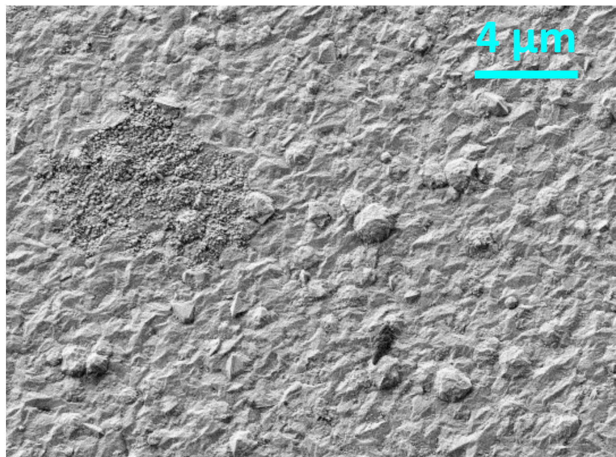
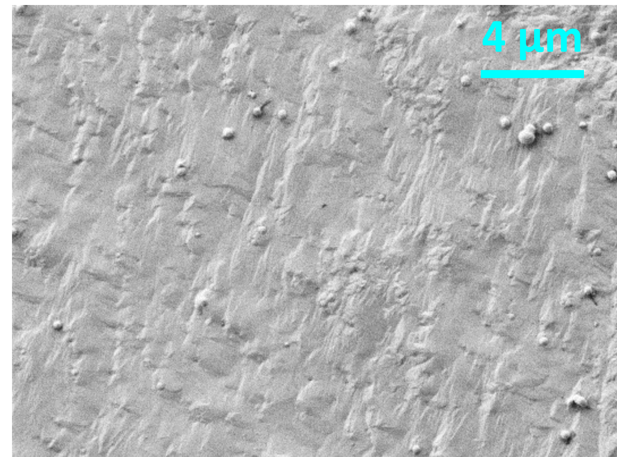
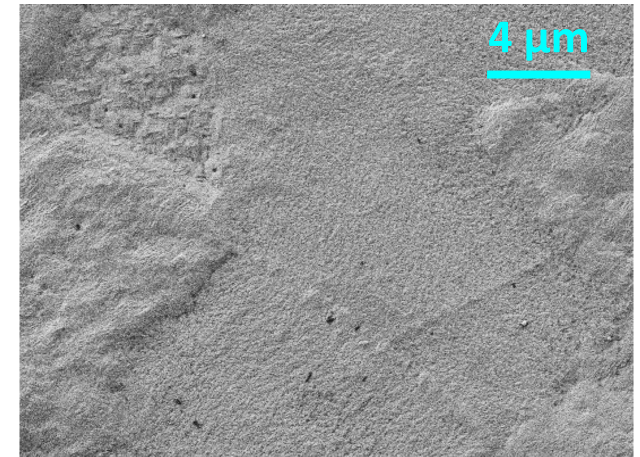


- Copper bath composition can enable specific properties of deposit e.g. grain size
- It is critical to keep bath close to nominal concentrations of all components
- Accurate, Repeatable and fast methods should be developed

- “Transforming WLP Applications: Introducing Cutting-Edge Next-Generation Nanotwinned Copper Processes to Revolutionize Hybrid Bonding”, Kyle Whitten, Journal of Microelectronics and Electronic Packaging, 2024, 21, 20–24
- “The influence of Cu microstructure on thermal budget in hybrid bonding”, IEEE ECTC, 2022, by L. Mirkarimi

Effects of Additives

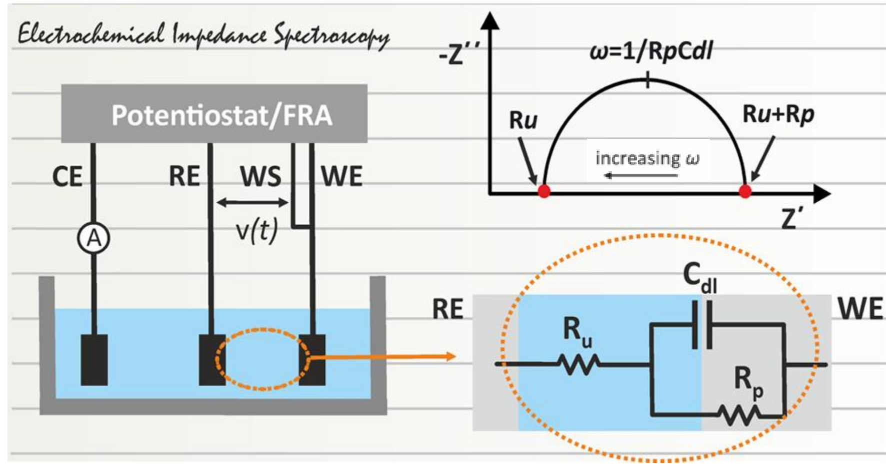
Microscopy of Copper Deposited from Baths with Different Additives

	Suppressor	Suppressor + Accelerator	Suppressor + Accelerator + Leveler
Optical			
SEM			
	Suppressor alone gives rougher textures	**Adding accelerator promotes more uniform grain**	**Three additives together make highly refined deposit, smaller grain, more uniform surface**

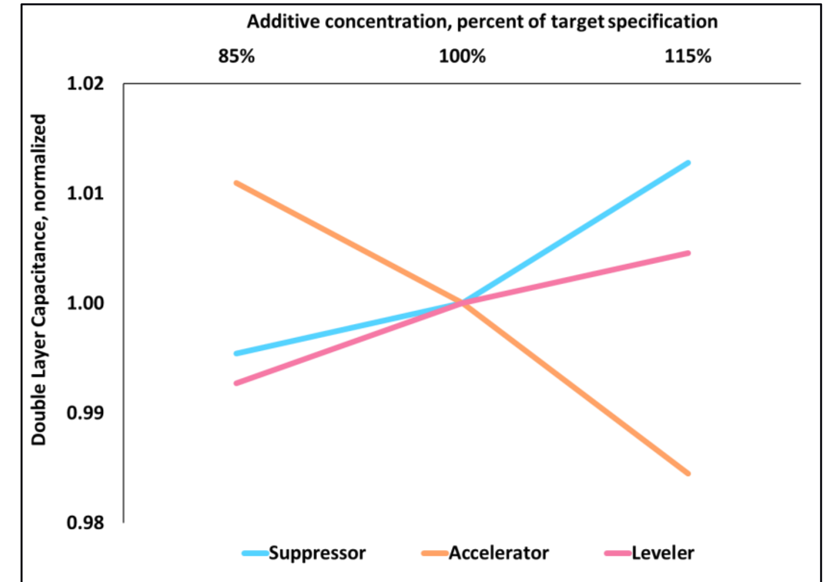
Optical microscopy: Meiji Techno MC-50 metallographic microscope; Scanning Electron Microscopy: commercial electron microscope

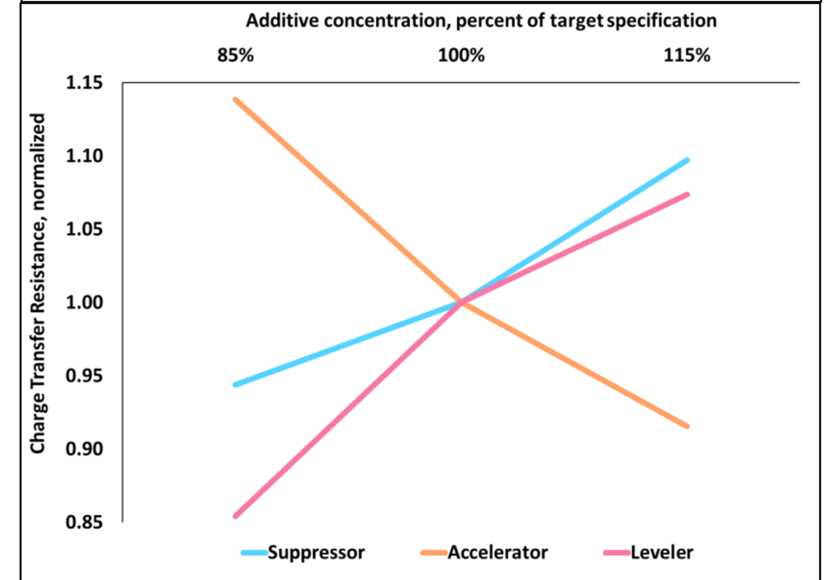
Characterization of Additives

Electrochemical Impedance Spectroscopy



- **Ru**=Solution resistance
- **Cdl**=double layer capacitance
- **Rp**=charge transfer resistance





- Charge transfer resistance and double layer capacitance are critical parameters to understand electroplating mechanism
  - Charge transfer resistance specifically focuses on the resistance associated with the actual electron transfer reaction occurring at the interface
  - Accelerator has dominant influence on both charge transfer resistance and double-layer capacitance promoting fine grain deposit
  - Leveler has a moderate impact and contributes to surface smoothness and uniformity
  - Suppressor has the least effect
- Nature and concentration of additives should be optimized to achieve desired plating results

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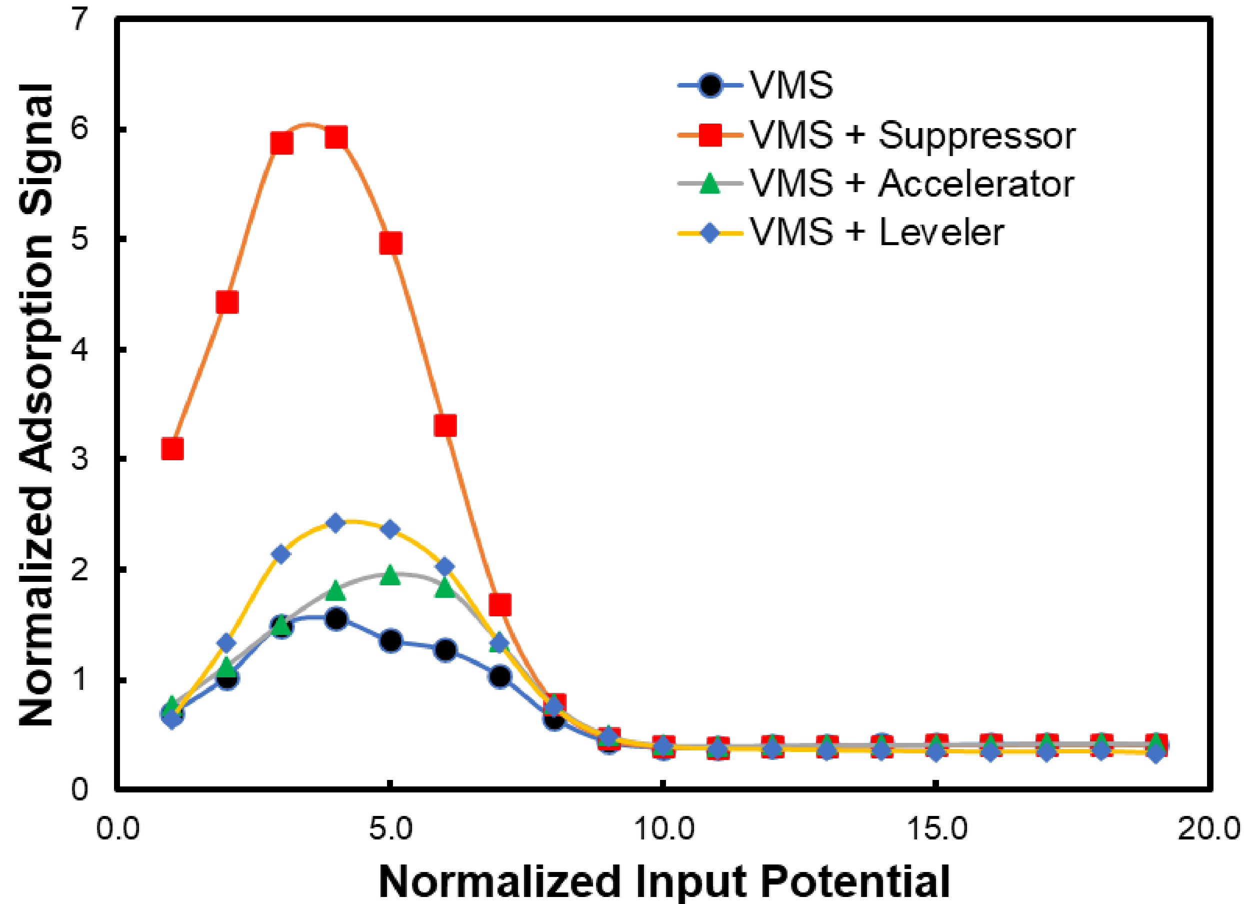
Behavior of Organic Additives

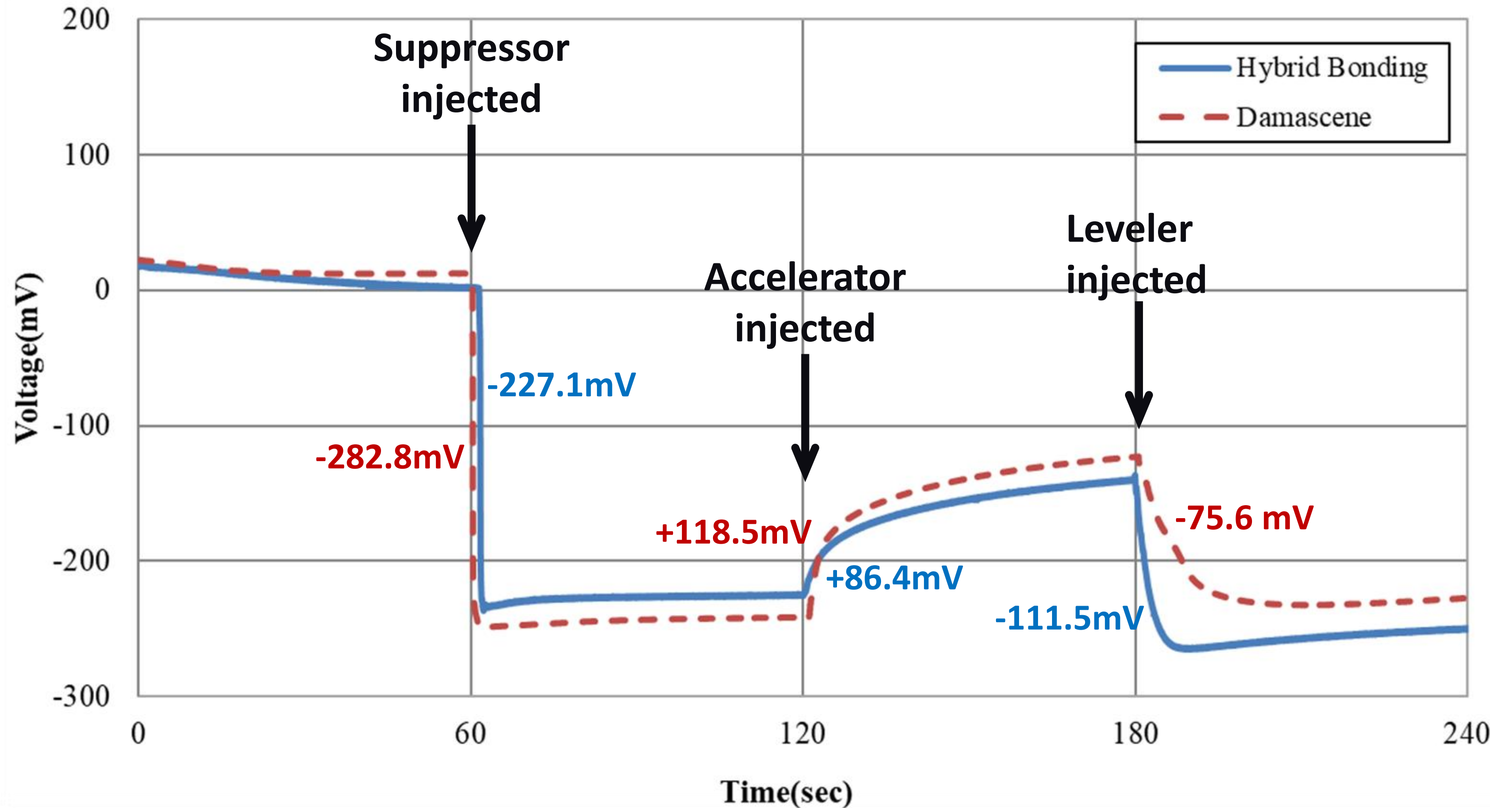
Electrochemical Impedance Spectroscopy, Mott-Schottky



- The impedance of the working-electrode interface is measured as a function of DC voltage
- This experimentation can help to optimize electrochemical settings for preferential adsorption conditions of organic additives

Characterization of Additives in Copper Plating Bath

Comparison of Different Baths



Potential Change, mV	Suppressor Injection	Accelerator Injection	Leveler Injection
Hybrid Bonding	227.1	86.4	111.5
Damascene	282.8	118.5	75.6

- New Copper plating bath contains weaker suppressor and stronger leveler, both acting as polarizers
- It is more difficult to separate and obtain accurate results with electrochemical techniques

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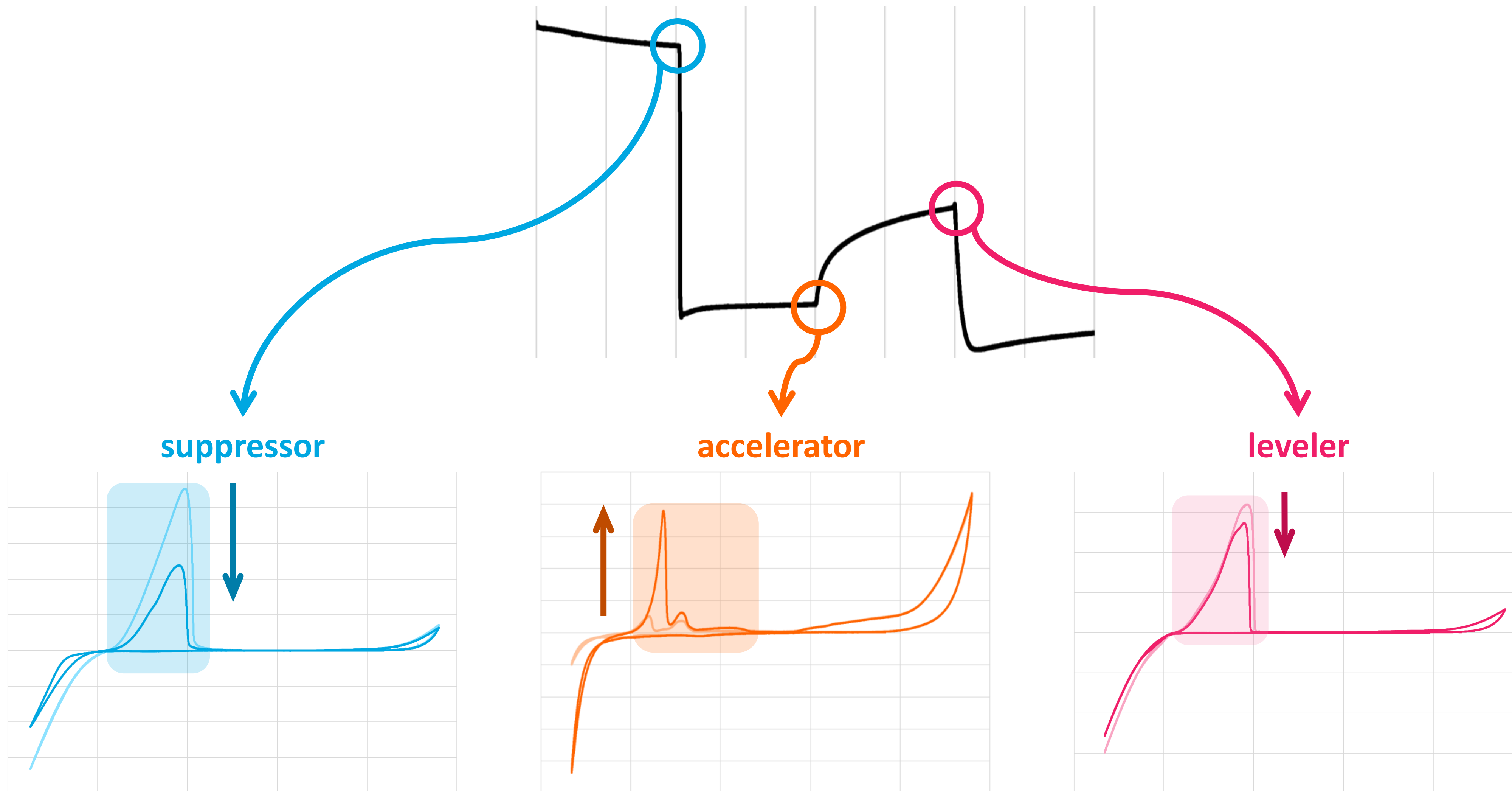
Summary of Electrochemical Effects of Additives in Copper Bath

Chronopotentiometry and CVS

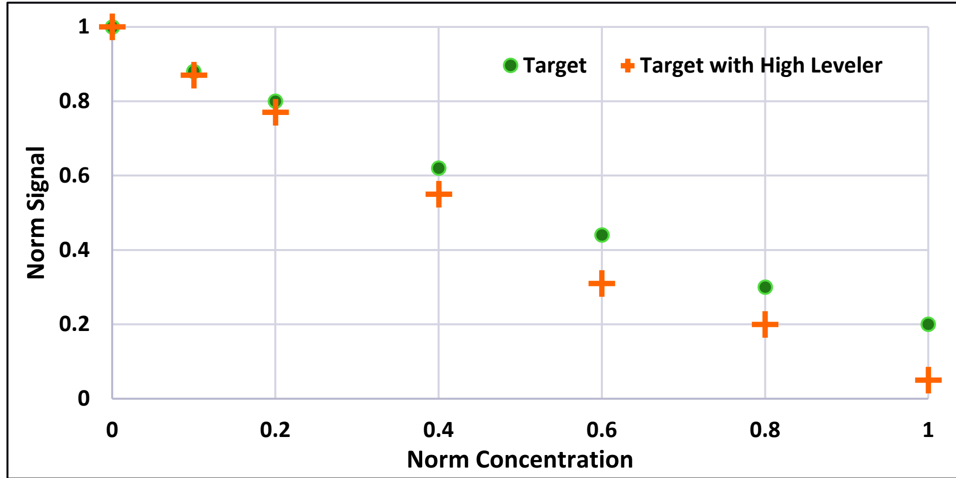


KLA QualiLab® benchtop plating bath analyzer; 3-electrode analysis cell with temperature control
Pt rotating disk electrode; Ag/AgCl reference electrode; counter-electrode

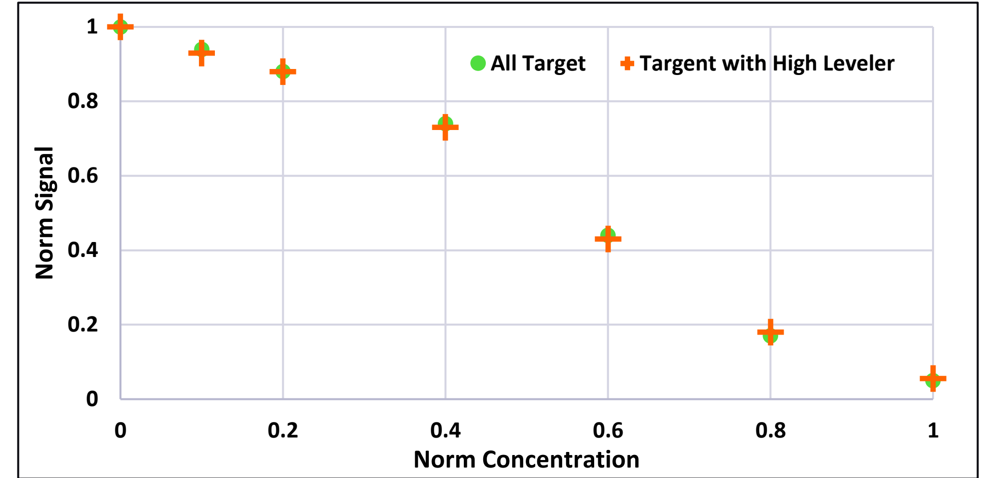
Development of CVS Analysis Methods

Suppressor and Leveler

Suppressor Traditional CVS Settings

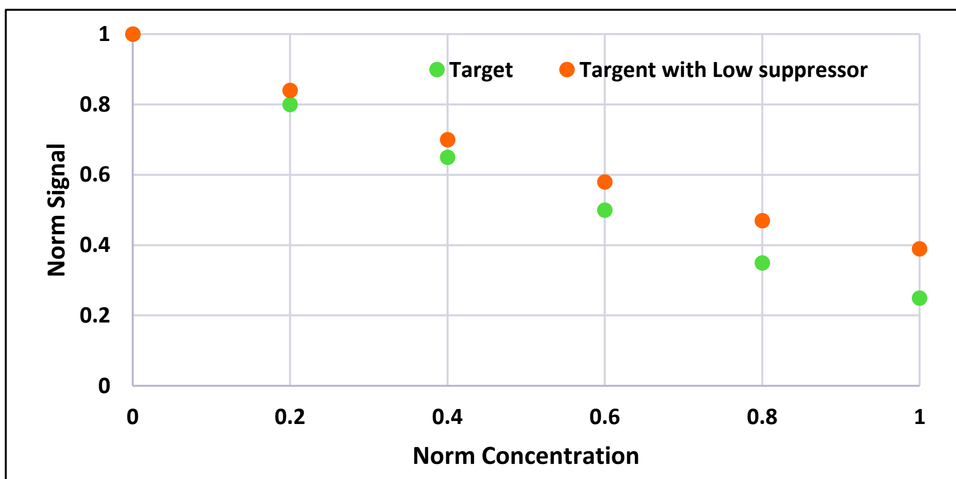


Suppressor New CVS Settings

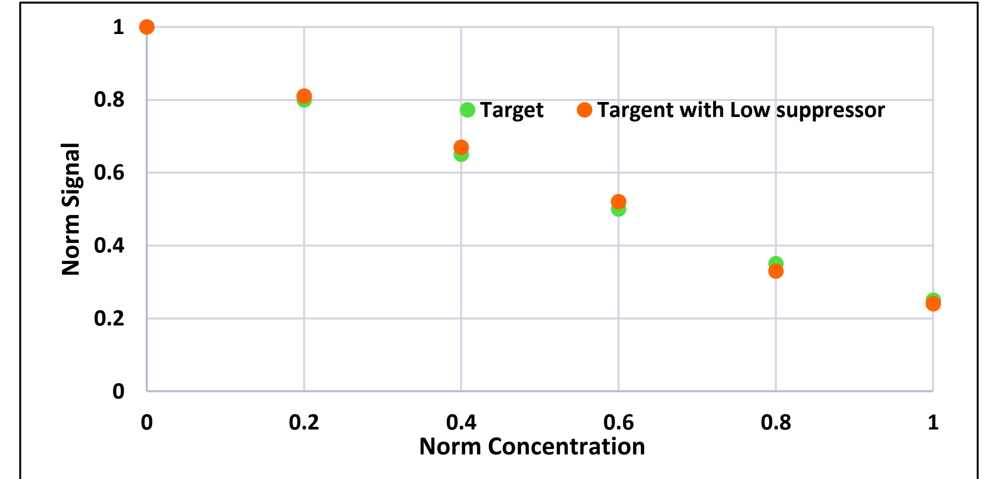


New Settings Eliminate interference between polarizing components

Leveler Traditional CVS Settings



Leveler New CVS Settings



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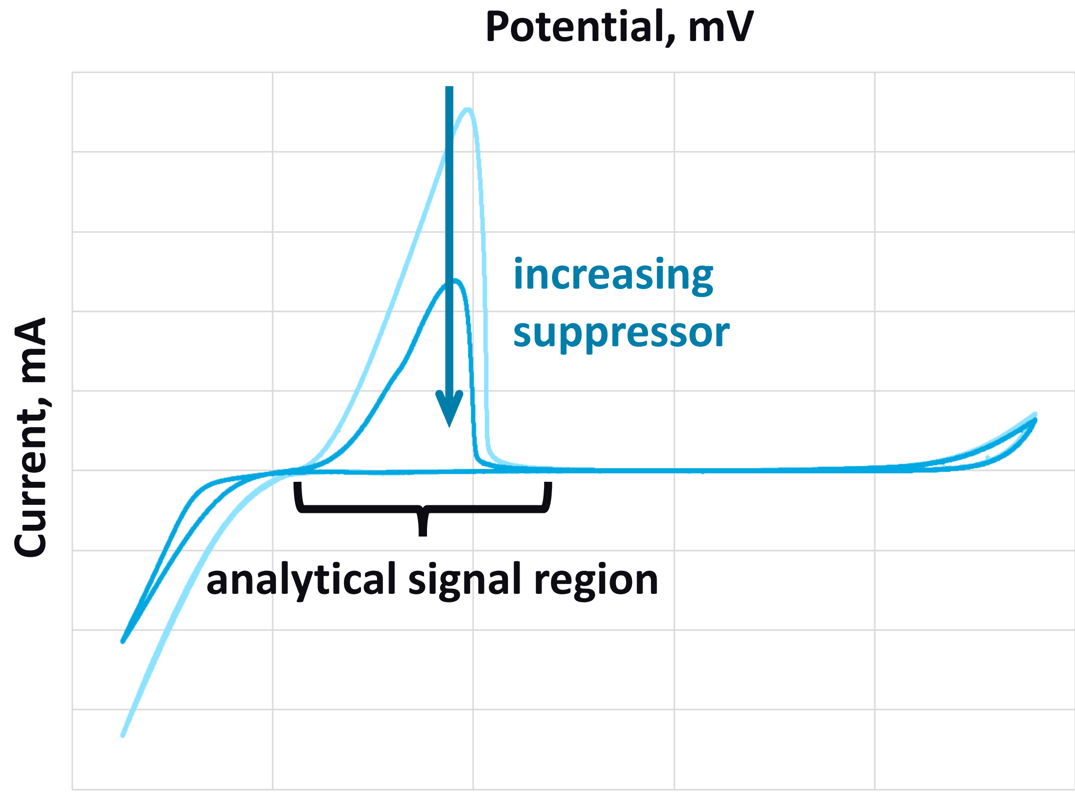
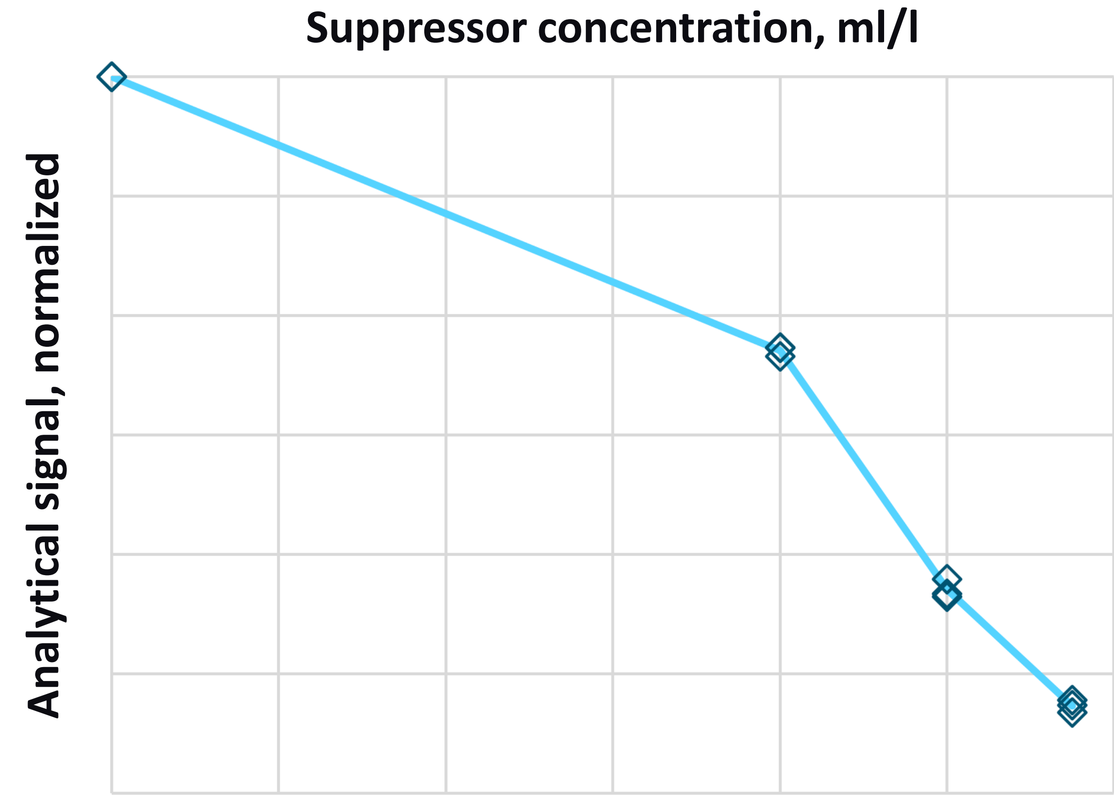
New CVS Analysis Methods

Suppressor Voltammogram and Calibration

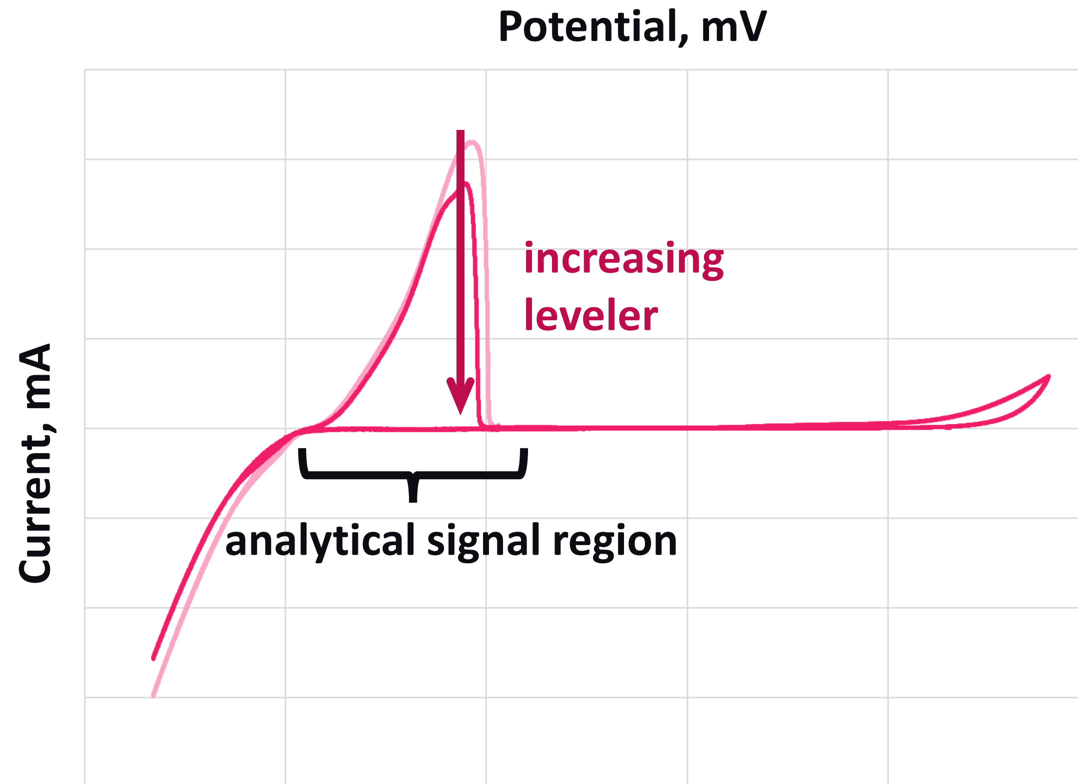


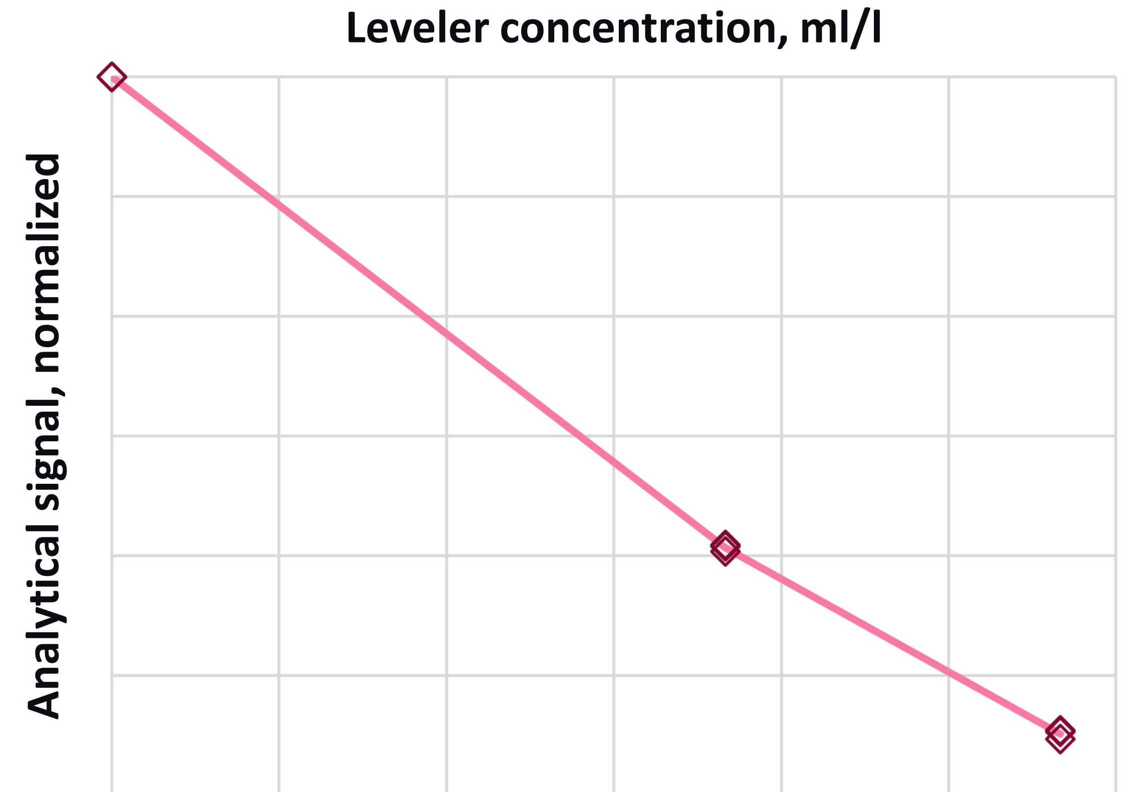


KLA QualiLab® benchtop plating bath analyzer; 3-electrode analysis cell with temperature control; Pt rotating disk electrode; reference Ag/AgCl electrode; stainless steel counter-electrode

New CVS Analysis Methods

Leveler Voltammogram and Calibration





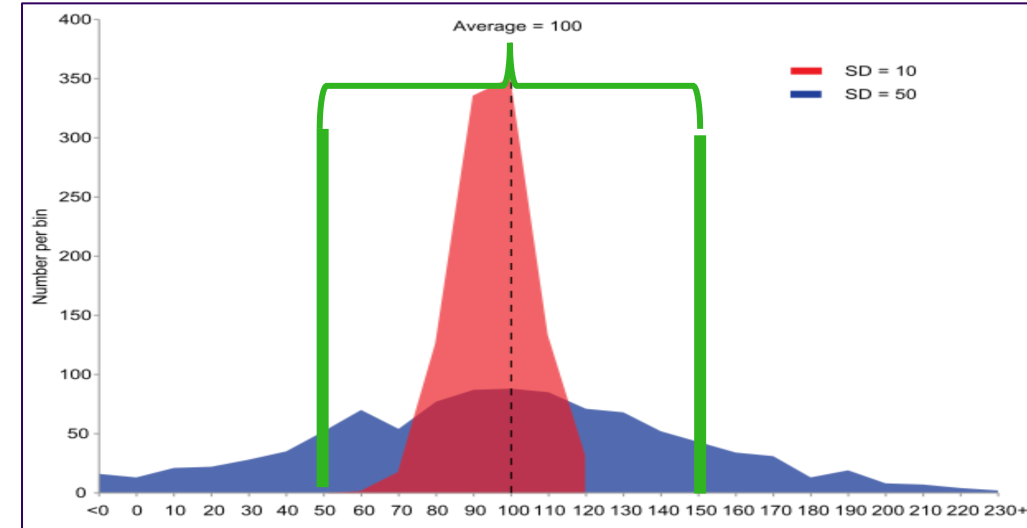
KLA QualiLab® benchtop plating bath analyzer; 3-electrode analysis cell with temperature control;
Pt rotating disk electrode; reference Ag/AgCl electrode; stainless steel counter-electrode

Analysis Considerations

Precision

- *Std Dev* = $\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i-\overline{x})^2}.$
- *RSD, % = Std Dev / Mean*
  - *(6*Std Dev / **PR**)*100 < 30*

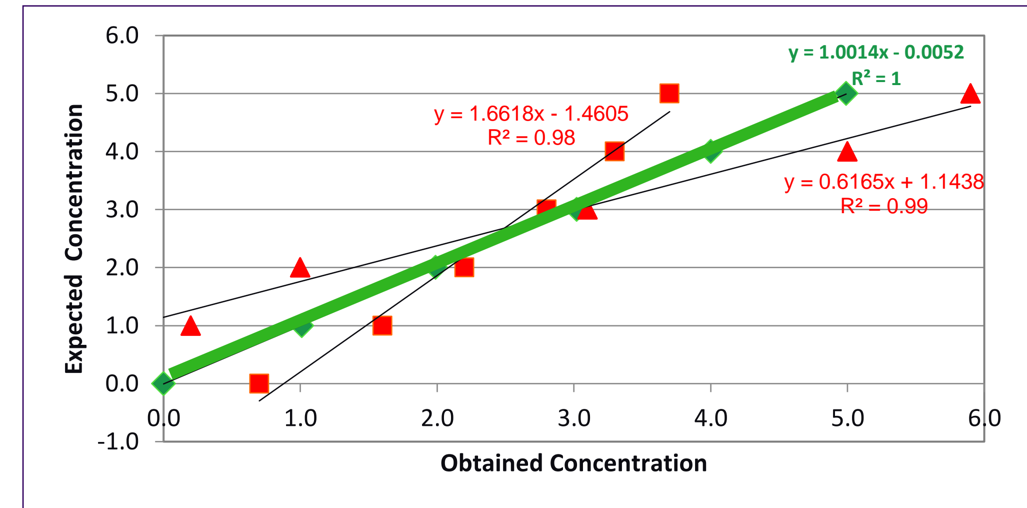
Process Range



Accuracy

- *Accuracy is the proximity of measurement results to the true value*
- *Accuracy % = (Mean-Expected)*100 / Expected*
- *Accuracy % = (Mean-Expected)*100 / **PR***

***PR** – Process Range*



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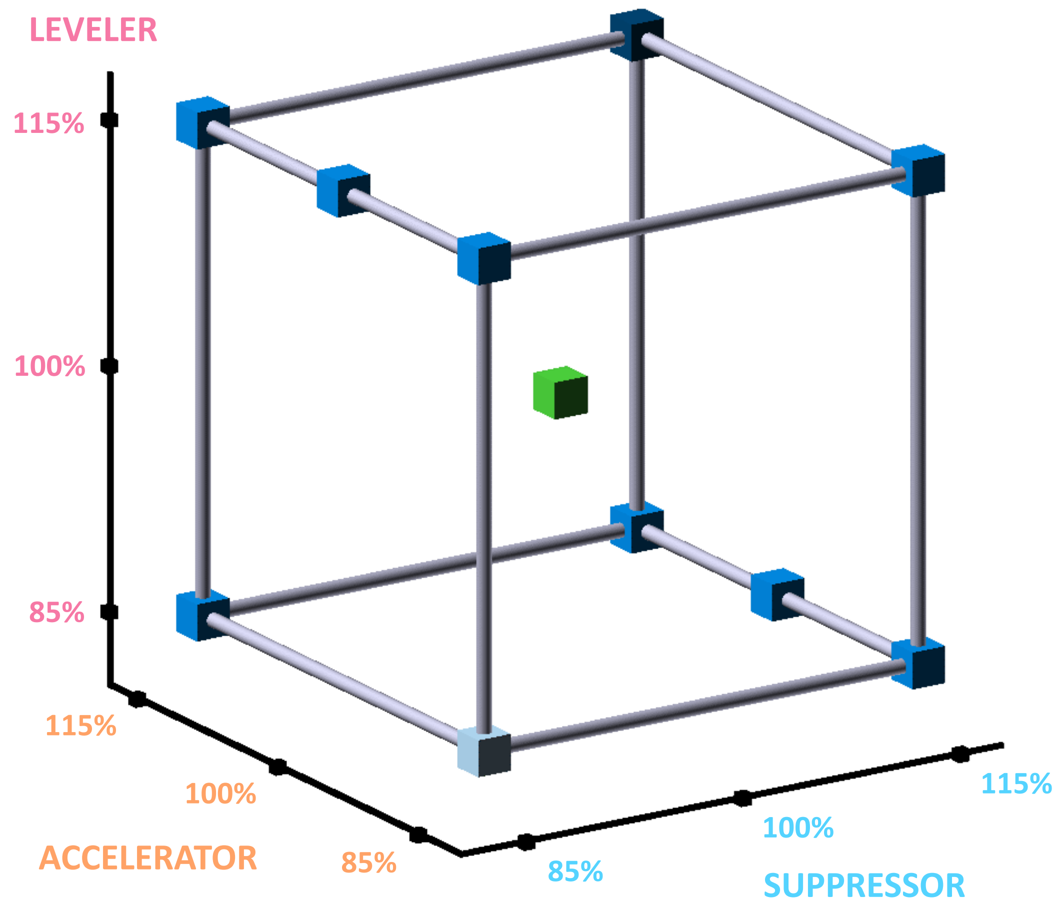
Performance of New Methods for Organic Additives

Benchtop Analyzer Results



- Samples were mixed using an augmented $2 \times 2 \times 2$ factorial design with inorganics at target levels
- Augmentation included varying inorganics levels
- All additives measured with replicates ($n \geq 3$)
- Developed settings were transferred to online analyzer

Online Analyzer Data

Additive	Accuracy, %	RSD, %
Accelerator	<2	<1
Suppressor	<2	<1
Leveler	<2	<1

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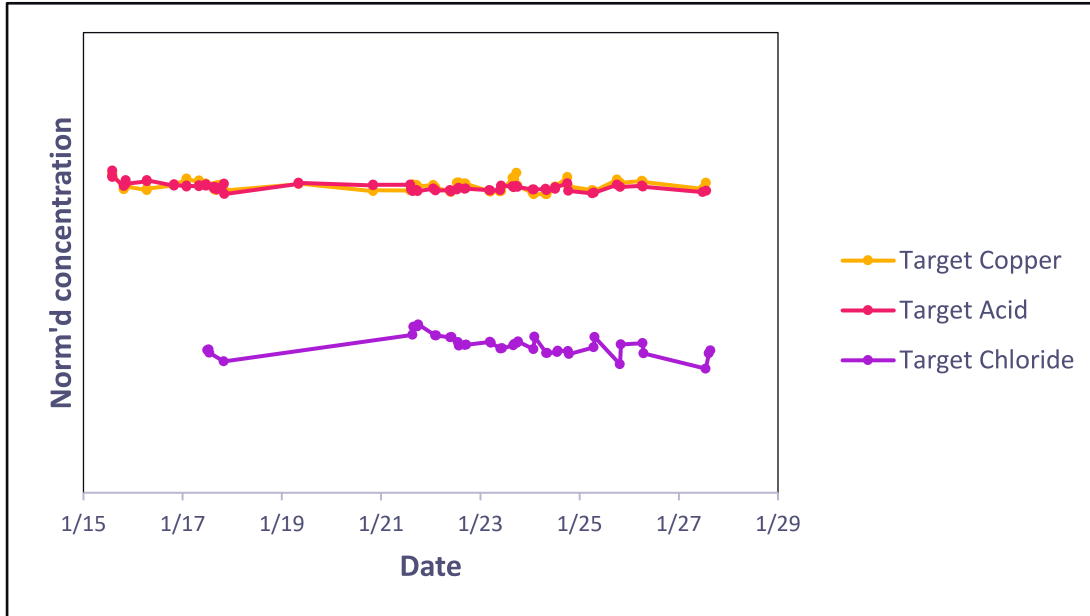
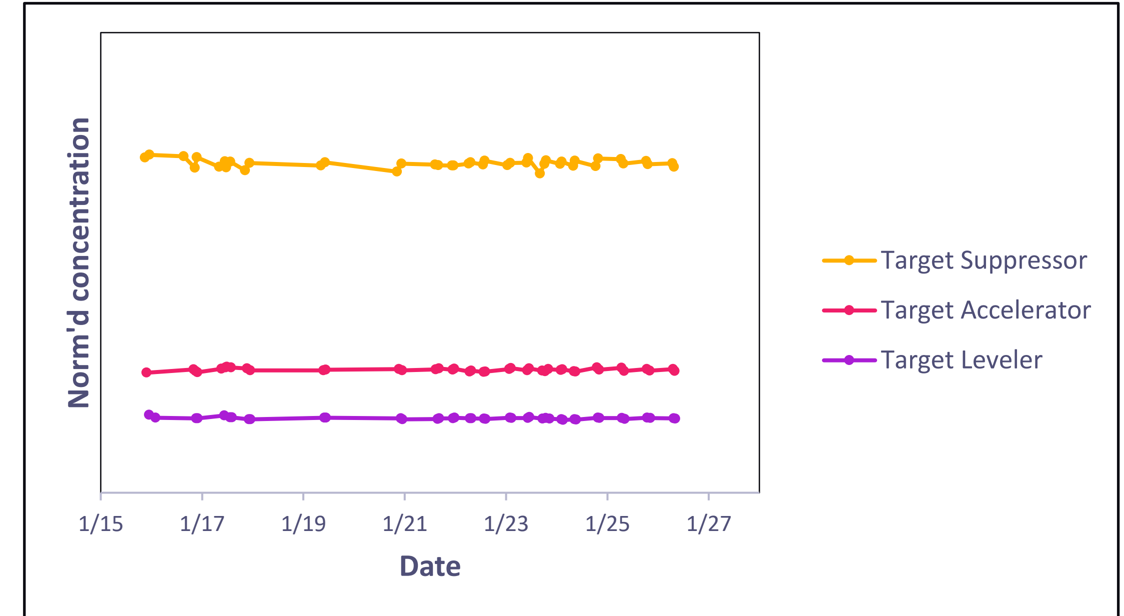
Online Analyzer Performance





Component	Accuracy (%)	Repeatability (%)
Cu	0.26	0.30
Acid	0.48	0.05
Chloride	0.03	0.10
Suppressor	0.36	0.78
Accelerator	1.45	0.53
Leveler	0.60	0.28

- Multiple Bath Concentrations tested
- Online Analyzer Results for target bath:
  - Accuracy <2.0%
  - Repeatability <1.0%

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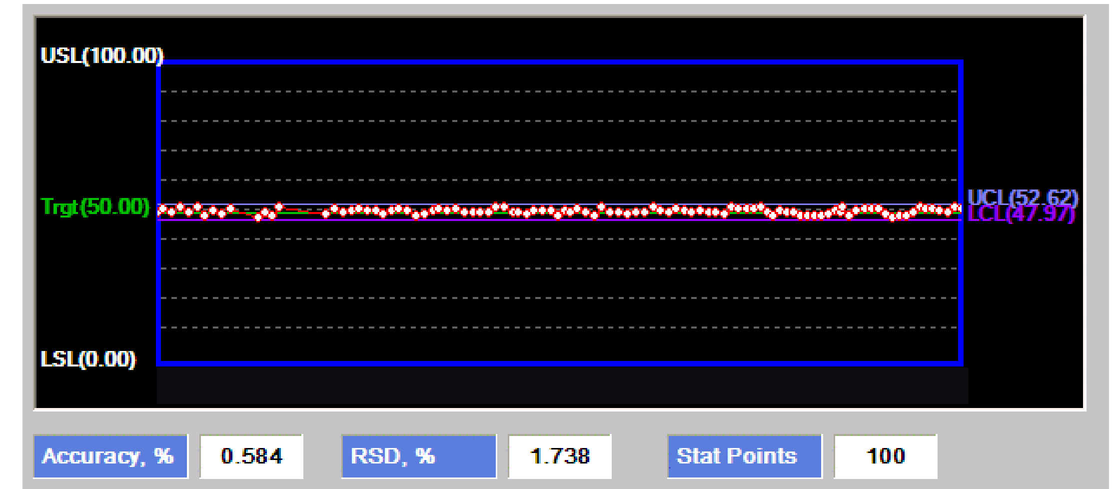
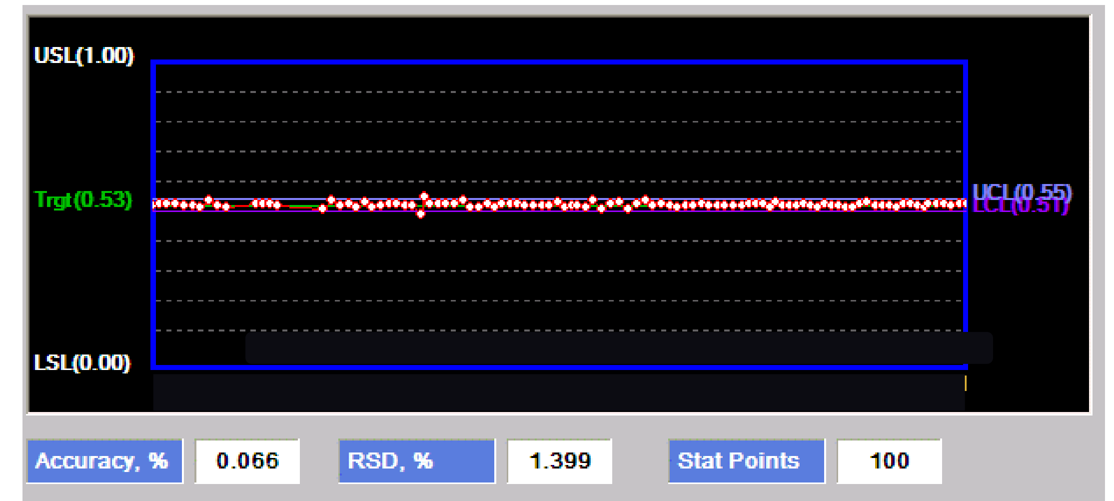
Plating Bath Control in Closed Loop

- Closed loop control of Organic Additive and Chloride (other components are not shown)
- Bath concentrations are maintained within 1%
  - Time span is one month

Chloride

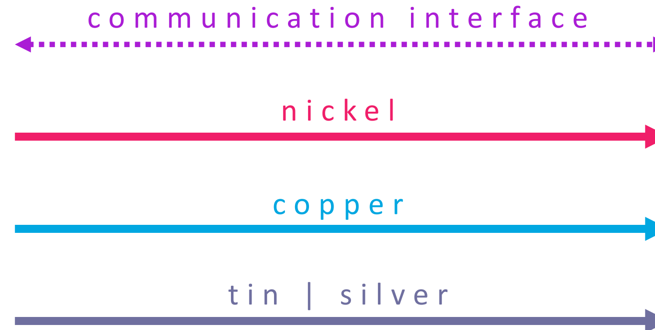


Organic Additive



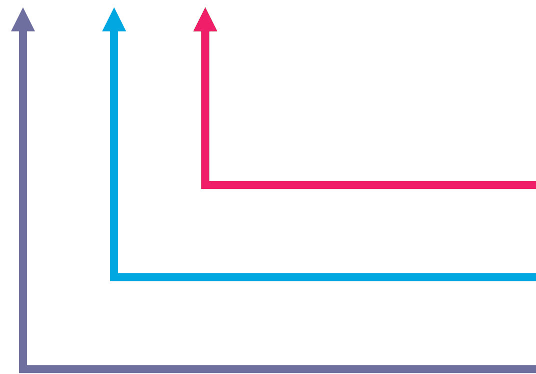
Online Process Integration

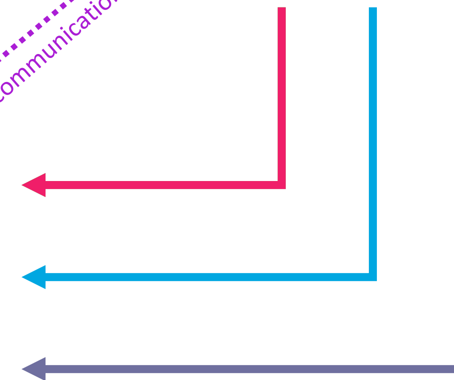
Enabling Closed Loop Monitoring and Control



Quali-Fill® Libra®

chemical management system





Quali-Dose®

chemical dosing system

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Conclusions

- Copper plating bath components interactions were studied and understood
- New analytical methods were developed for benchtop and online analyzers
- New methods reveal accuracy within 2.0% and repeatability within 1.0% when online analyzer is utilized

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Acknowledgements

- The authors thank:
  - Mandar Paranjape for organizing Scanning Electron Microscope imaging
  - Zhi Liu for extended testing of methods performance on an online analyzer
  - Victoria Paluch for help with optical microscopy
  - Nila Patel for help with optical microscopy
  - Yevgeny Lifshitz for advice on presenting data

Thank you!

Q&A