

# ***Surface Contamination Control through Final Surface Finish (FSF™) Processing for Semiconductor Equipment Parts for Sub-16 Nanometer Nodes***

*Ardeshir “Ardy” J. Sidhwa Ph.D., Osama Khalil, John Deem,  
David Zuck, Matthew House  
Innovation and Technology (R&D)  
1900 AM Drive, Suite 200  
Quantum Global Technologies, LLC  
Quakertown, PA, USA*

Contact info: [ardy.sidhwa@quantumclean.com](mailto:ardy.sidhwa@quantumclean.com), Mobile: 602-499-6510

# ***Abstract***

- Meeting defectivity requirements are challenging as technology nodes continue to scale down. Defect variability such as particles and residues create killer defects at the component-level and is expected to severely impact product yields at sub-16 nm technology nodes. Additional complexity, in the form of new processes and materials, will further challenge component-level design and performance.
- Quantum Global Technologies® (QGT: Quantum Clean® & ChemTrace®), a leader in the semiconductor parts cleaning and analytical business through their Final Surface Finish (FSF™) processes, has developed new technologies aimed at exceeding OEM performance and meeting stringent defectivity requirements for sub-16 nm technologies.
- This work addresses some of the major challenges and solutions towards achieving contamination-free manufacturing (CFM) in a cost-effective manner.

# ***Experimental Setup for FSF™***

- Final Surface Finish (FSSF™) was developed to clean different substrates precisely. Substrate material can vary from aluminum, stainless steel, titanium, ceramic, quartz, ceramic coating, etc.
- To further complicate the surface condition, the substrate can be textured or non-textured material. However, textured material introduces additional complexity to the trace metal analysis due to increased surface area from surface morphology. During the parts cleaning process each substrate is exposed to multiple process parameters.
- Figure-1 depicts the above scenario in graphical format. The ultimate goal is to yield the best possible Final Surface Finish (FSF™) for critical substrates.

# Graphical Presentation Format for FSF™

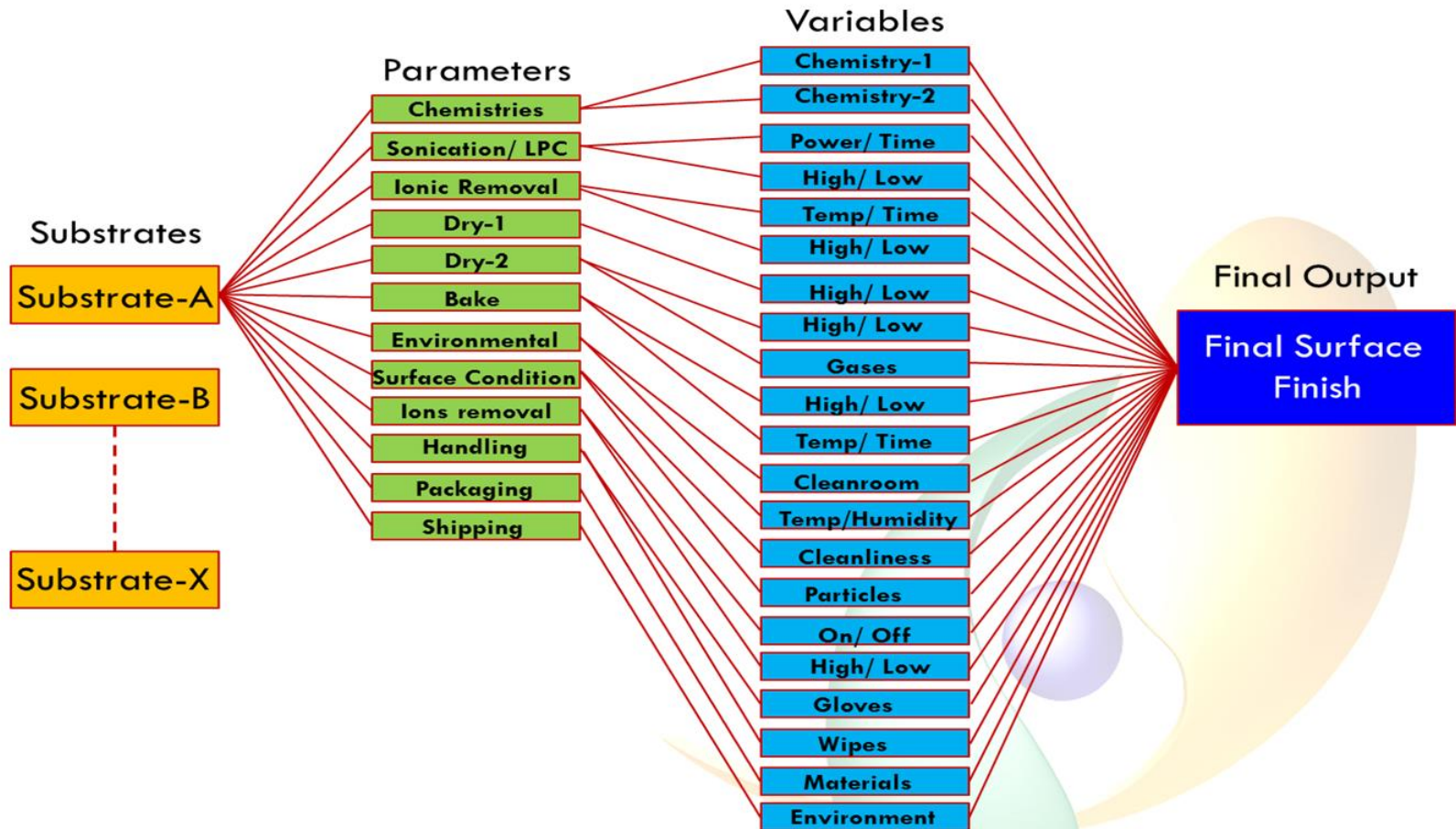


Figure-1: Experimental pathway for developing FSF™ recipe builder

# ***Introduction to Final Surface Finish (FSF™)***

- In order to confront the issue of adapting parts cleaning technology to shrinking critical dimensions of integrated circuitry, a pathway to achieving atomically clean surfaces through experimentation was defined. Key process parameters that affect surface cleanliness metrics that were identified were first evaluated within an experimental parametric space that would serve as a baseline for improvements made to the final surface treatment process. It is imperative that OPC facilities unify analogous processes so they are consistent and copied exactly to reduce variability and maintain the quality that is expected by the customer, regardless of the cleaning site.
- For QuantumClean, this meant that research was to be targeted at comparing and selecting the best chemical treatments, surface passivation, texturing, and coating techniques, and cleanroom protocol to be developed and carried out at all sites.

# ***Final Surface Finish (FSF™)- cont'd***

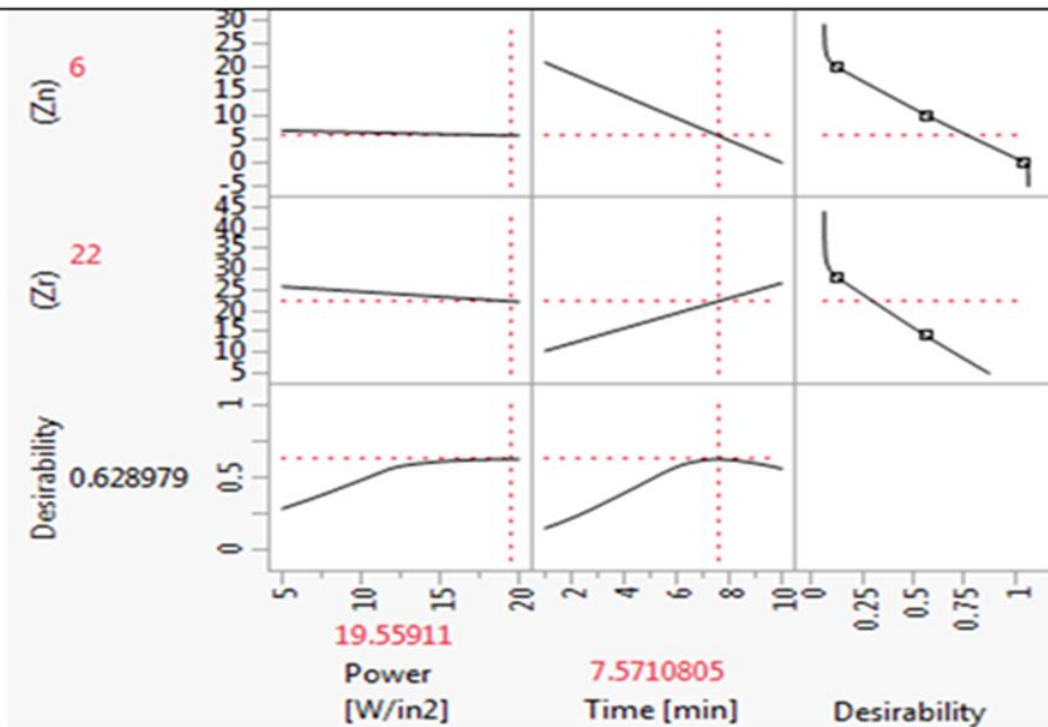
- OEMs and customers create the specifications that define their surface cleanliness acceptance criteria. For example, a specification for surface trace metals defines the maximum count of leachable metals for a part acceptable for installation after a clean.
- To screen the effects of altering process steps on surface trace metals, a “progressive” experimental design was implemented, in which process steps are optimized in phases, then optima from each phase are transferred to the next phase until all factors and process steps are optimized. In the present work, each phase is a full-factorial experiment centered upon a single process step. Table I presents the phase structure of the FSF experiments. The output to these tests were a combination of 30 element trace metal analysis by inductively-coupled plasma mass spectrometry (ICP-MS), and ion chromatography by deionized water extraction.

# ***Final Surface Finish (FSF™)- cont'd***

- From these data, linear regressions were generated relating each experimental factor to model-predicted outcomes of each trace metal or ionic contaminant. For any given configuration of process parameters within the experimental parametric space, a set of regression models can predict the counts of each element or ionic compound. The measure of goodness for a particular configuration of factor levels, or desirability, is a function used to describe the minimization of contaminants on a scale from zero to one. Desirability functions were designed such that maximum desirability (lower target limit) is set to the lower detection limit of the measurement instrument, while the upper target limit is set to the average metal or ion count within the experiment.
- Figure 2 shows an example of how process parameters applied power and immersion time were tuned so to maximize the desirability function for a particular phase of quartz experimentation. Only two elements are shown in Figure 4 (zinc and zirconium), but all 30 trace metals analyzed by ICP-MS are accounted into each desirability function.

Cleaning Process Step	Process Parameters Used By Phase				
	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Final Chemical Treatment		P1 Optimum Chemistry	P1 Opt. Chem.	P1 Opt. Chem.	P1 Opt. Chem.
Cleanroom Step 1	POR Step 1		P2 Opt. CR Step 1	P2 Opt. CR Step 1	P2 Opt. CR Step 1
Cleanroom Step 2	POR Step 2	POR Step 2		P3 Opt. CR Step 2	P3 Opt. CR Step 2
Cleanroom Step 3	POR Step 3	POR Step 3	POR Step 3		P4 Opt. CR Step 3
Packaging	POR Pkg	POR Pkg	POR Pkg	POR Pkg	

**TABLE-1: PROGRESSIVE OPTIMIZATION EXPERIMENT DESIGN**

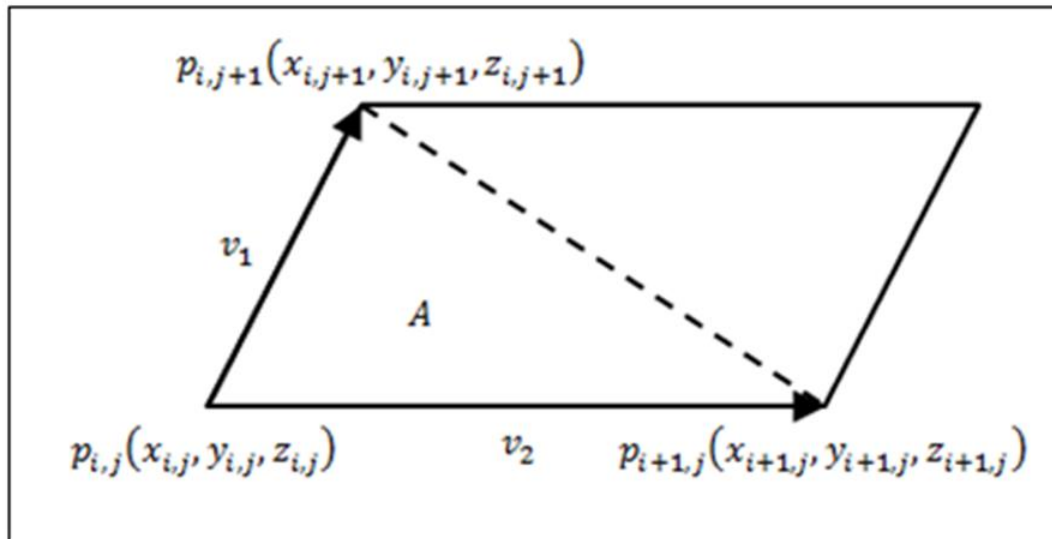


**Figure-2: A section of the array of regression plots and desirability functions (top two rows, showing regressions for zinc and zirconium). Dotted crosshairs indicate the values of each element and desirability function when the factors power and time are set to maximize desirability.**

# ***Surface Texture Compensation***

- When considering trace metallic or ionic contaminants, it is important to consider that the test method for acquiring these data involves an approximation of the macroscopic surface area from which the leachable metals are extracted, in order to report data in units of contaminants per unit area. However, the microscopic surface area of a textured surface can be much greater than that of a non-textured or polished surface, therefore subjecting textured parts to the same specification for contaminants per macroscopic surface area leaves those parts at a disadvantage. To address this issue, models were formulated to approximate microscopic surface areas of materials subjected to grit blasting from a given grit size or  $R_a$ . Samples of aluminum, titanium, stainless steel and quartz textured to roughnesses prevalent in QuantumClean grit blast procedures were analyzed by optical profilometry (Zemetrics ZeScope) and validated by 408-nanometer laser scanning microscope (Keyence VK-X250).

- Figure 3 shows Zometrics ZeScope optical profilometer outputs  $z$  values on an  $x,y$  array, so to numerically compute surface area,  $\{x,y,z\}$  values on the captured array are used to construct a polyhedral surface constituent of polygons of calculable area  $A$ , according to Equation 1, where a half parallelogram is constructed from data points  $p_{i,j}(x_{i,j}, y_{i,j}, z_{i,j})$ ,  $p_{i+1,j}(x_{i+1,j}, y_{i+1,j}, z_{i+1,j})$ , and  $p_{i,j+1}(x_{i,j+1}, y_{i,j+1}, z_{i,j+1})$ .



$$A = \frac{1}{2} |\mathbf{v}_1 \times \mathbf{v}_2|$$

Where  $\mathbf{v}_1 = p_{i,j+1} - p_{i,j}$  and  $\mathbf{v}_2 = p_{i+1,j} - p_{i,j}$ .

Figure 3: A parallelogram formed by the two vectors  $\mathbf{v}_1$  and  $\mathbf{v}_2$  used to calculate area  $A$ .

- Total area is the summation of all values of  $A$  within the assay array. The model resulting from performing this calculation on any variety of part surfaces adds a major component to the FSF™ Recipe Builder that now accounts for microscopic morphology that is intrinsic to part surfaces, yet affects contamination measurements and parts cleaning first-pass yield. Figure 4 depicts the Surface morphology maps of non-textured, lightly textured and heavily textured quartz material. Figure-5 depicts normalized computed microscopic surface area of non-textured versus textured stainless steel.

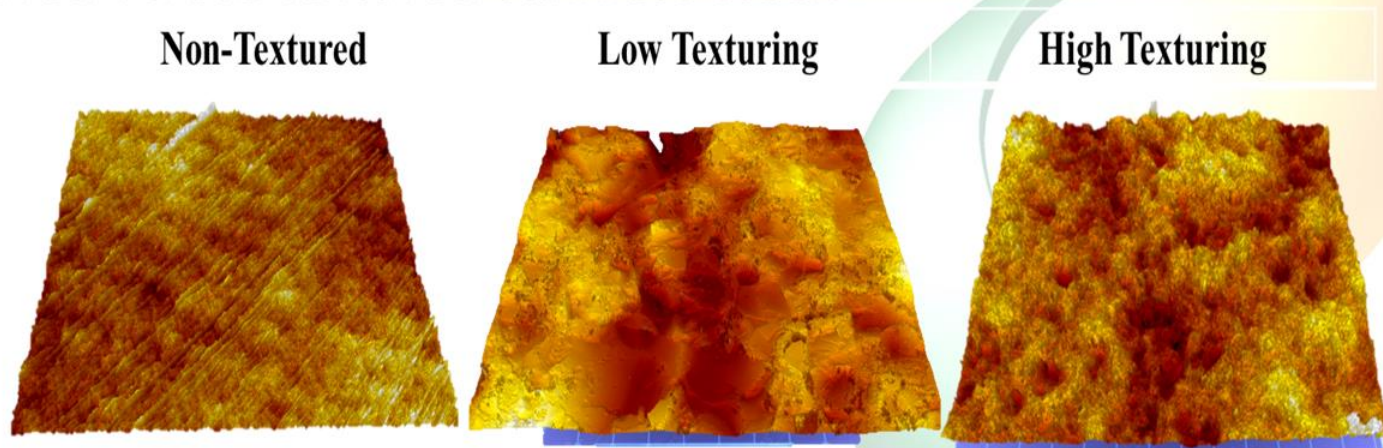
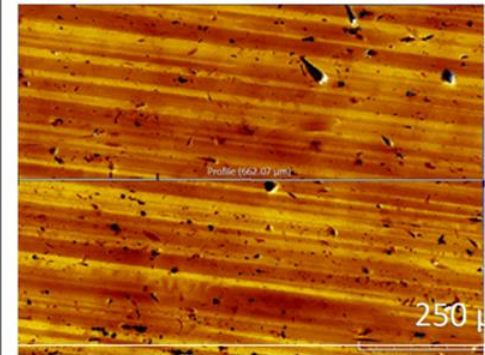
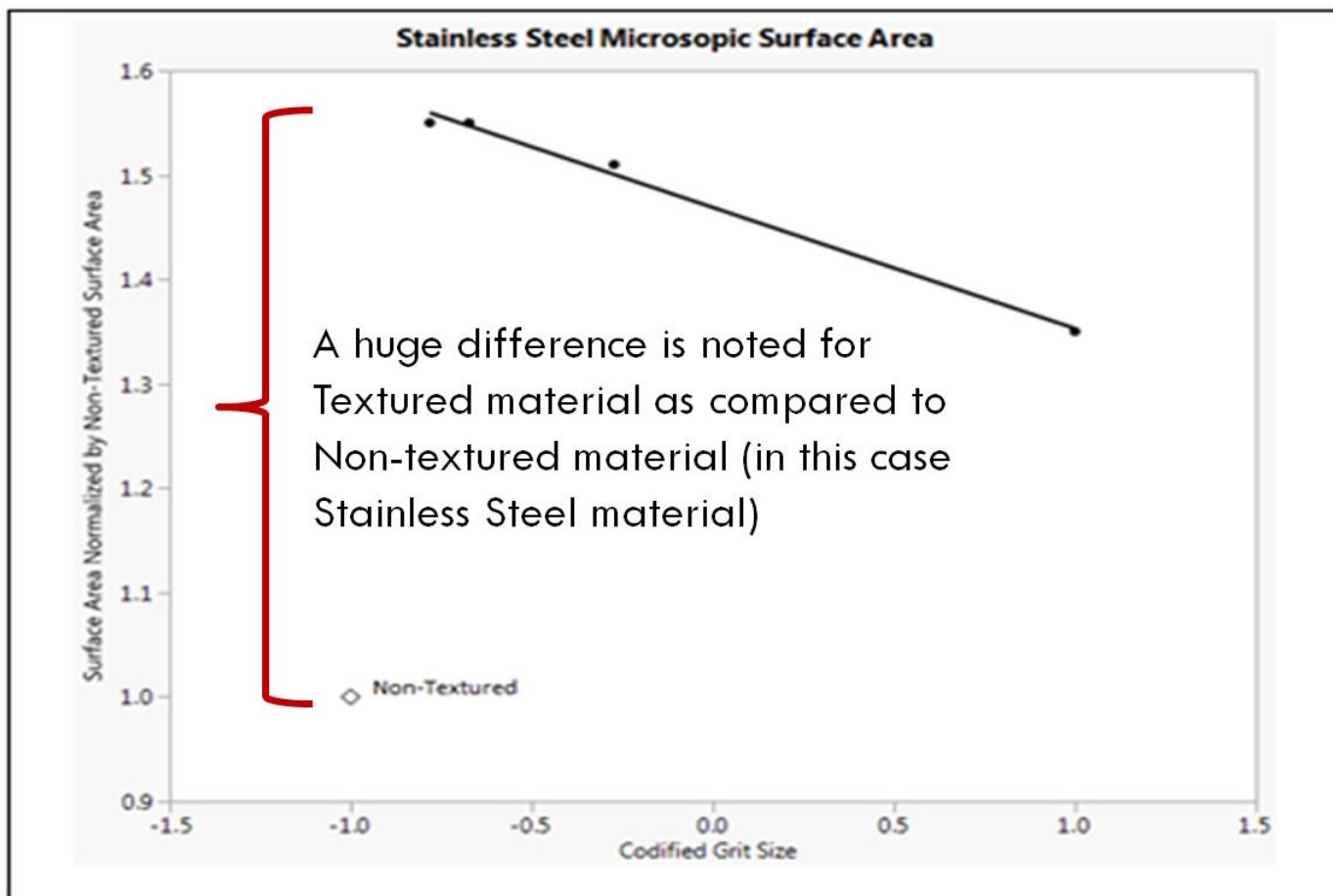
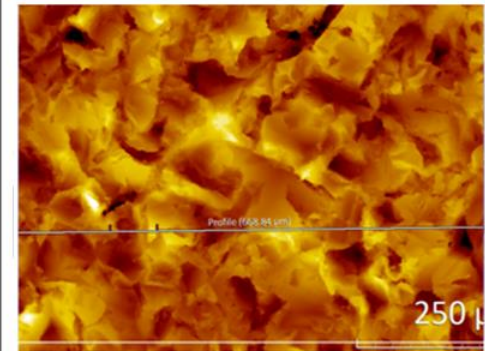


Figure 4: Surface morphology maps of non-textured, lightly textured, and heavily textured quartz captured by Zometrics ZeScope optical profilometry.



**Non-Textured**



**Textured**

Figure 5: Computed microscopic surface area of textured stainless steel, normalized by non-textured surface area and measured by Zometrics ZeScope optical profilometry related to codified grit sizes ranging from -1 to +1

# ***Results and Discussion***

- Table 2 presents the codified results of the Final Surface Finish progressive optimization experimental process (actual process parameter values converted to -1 to 1 scale). These values have been used as a reference datum for subsequent efforts to mitigate trace metallic and ionic contamination. The chemical composition column of Table 2 shows a majority of substrates performing best under Chemistry B. This may be indicative of an opportunity to unify cleaning processes, which can drive down the cost of consumables associated with each of those substrates.
- Figure 6 presents the trace metal improvement with Chemistry B from the process baseline. Given the sensitivity of sub-20 nanometer processes and that of surface cleanliness measurement systems, process development for sub-20 nanometer surface cleaning requires this kind of baseline reference in order to confidently determine whether a new process makes measureable improvements. Every time the FSF™ processes are improved by a new finding, baseline defectivity falls to a new low. Figure 7 shows actual results of FSF™ process

	Chemistry		Cleanroom Step 1		Cleanroom Step 2		Cleanroom Step 3	Package
	Comp.	Time	Set	Time	Set	Time	Type	Procedure
	Chem-A	-1	-1	-1	-1	-1	A	Bag-A
	Chem-B	0	+1	+1	+1	+1	B	Bag-B
Levels	Chem-C	+1						Bag-C
Textured Aluminum	Chem-B	+0.65	-1.00	-0.08	+0.75	+0.96	A	Bag-B
Non-Textured Aluminum	Chem-A	+0.66	+0.21	-0.55	+0.94	+0.86	A	Bag-B
Textured Titanium	Chem-B	+0.35	+1.00	+1.00	-0.96	+1.00	A	Bag-B
Non-Textured Titanium	Chem-A	+0.44	-1.00	+1.00	+0.44	-1.00	A	Bag-B
Textured SST	Chem-B	+1.00	-0.15	+1.00	-1.00	+1.00	A	Bag-B
Non-Textured SST	Chem-B	+1.00	+1.00	+1.00	+1.00	+1.00	A	Bag-B
Textured Quartz	Chem-B	+1.00	+1.00	+1.00	-1.00	-1.00	A	Bag-B
Non-Textured Quartz	Chem-B	+1.00	+0.97	+0.32	+1.00	+0.88	A	Bag-B
Anodized Aluminum	Chem-B	-1.00	+1.00	-1.00	+1.00	+0.91	A	Bag-B
Alumina (Ceramic)	Chem-B	+0.03	+1.00	+1.00	-1.00	+1.00	A	Bag-B
Bulk Yttria	Chem-C	+0.02	-0.98	+1.00	-1.00	-1.00	A	Bag-B

TABLE-2: OPTIMIZED PROCESS PARAMETER LEVELS BY SUBSTRATE

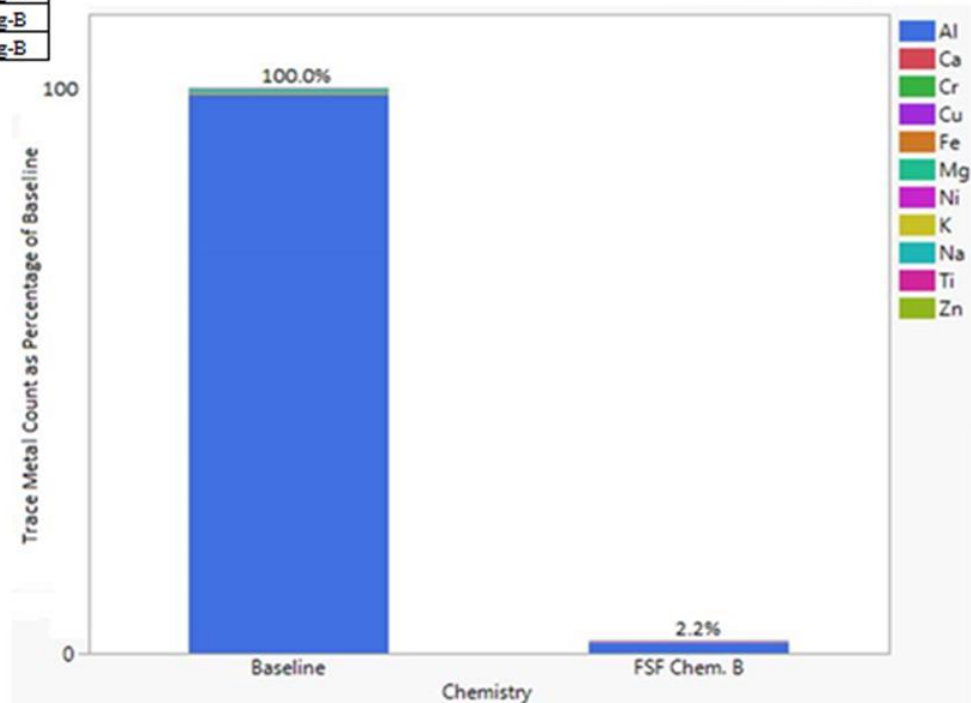


Figure-6: Trace metal results comparing new test chemistries to FSF baseline for non-textured aluminum cleaning

## Final Surface Finish (FSF™) for Aluminum Substrate

	OEM-1 Spec			OEM-2 Spec					QC-Historical			
$10^{10}$ atom/cm <sup>2</sup>	Non-Textured 6061 Al Part-A	Non-Textured 6061 Al Part-B	Critical Aluminum Part (AL6061-T6) Part-C	Non-Textured 6061 Al Spec PART-AB	FSF Validation-1	FSF Validation-2	FSF Revalidation Multiple Samples	Predicted Value	Part-A	Part-B	Part-C	Part-AB
Element	Part-A	Part-B	Part-C	Part-AB	Batch-1	Batch-2	Multiple-Batches	Values from Simulation	Control Data	Control Data	Control Data	Control Data
Al	100,000	100,000	220,000		9,900	4,200	6,500	12,466	96,418	39,571	219,222	
Ca	1,500	1,500	1,500	5,000	85	140	400	157	516	1,300	674	584
Cr	200	200	250		20	20	20	20	69	20	135	
Co				100	5	5	5	5				87
Cu	5,000	5,000	5,000		98	110	360	224	2,458	66	38	
Fe	5,000	5,000	5,000		21	20	53	38	4,366	182	572	
Pb					3	3	3	3				
Li				1,000	10	20	20	10				795
Mg	5,000	5,000	5,000		660	300	330	1,566	4,882	1,223	2,305	
Mn					6	5	5	1				
Mo				100	2	2	2	2				79
Ni	100	500	100	2,000	11	10	10	10	25	97	238	146
K	400	400	400	5,000	50	150	50	50	105	367	107	345
Na	2,000	2,000	2,000	10,000	50	210	170	94	1,690	1,040	409	1,469
Sn					5	11	5	5				
Ti	25	100	250		20	20	20	20	33	28	125	
Zn	120	350	500		27	20	20	40	378	596	212	

20nm, 16nm and 14nm  
OEM Specifications

Final Surface Finish Data

Actual 20nm, 16nm and 14nm  
Parts Data

Figure-7: Shows actual FSF™ data compared to current specification requirements

# ***Summary and Conclusion***

- Parts cleaning requirements have changed significantly since they were originally outsourced to specialized third parties. These changes are driven through increasing numbers and combinations of materials and processes that allow improvements in device performance and footprint reduction.
- Trace metal, ionic and particulate contamination levels that are near or even beyond current metrology capability are now found to be major impediments to chamber process performance and device yield - “Things that didn’t matter before now do”.
- The challenges moving forward include the development of increasingly complex selective stripping technologies, improved handling and packaging solutions and continued improvements in real-time metrology that can detect ever smaller contamination levels and allow predictable chamber performance to help drive the industry forward.