Insights into c-Si Processing for Photovoltaic Applications

Ismail Kashkoush and David Jimenez

PAG Meeting, Semicon West, July 15, 2010

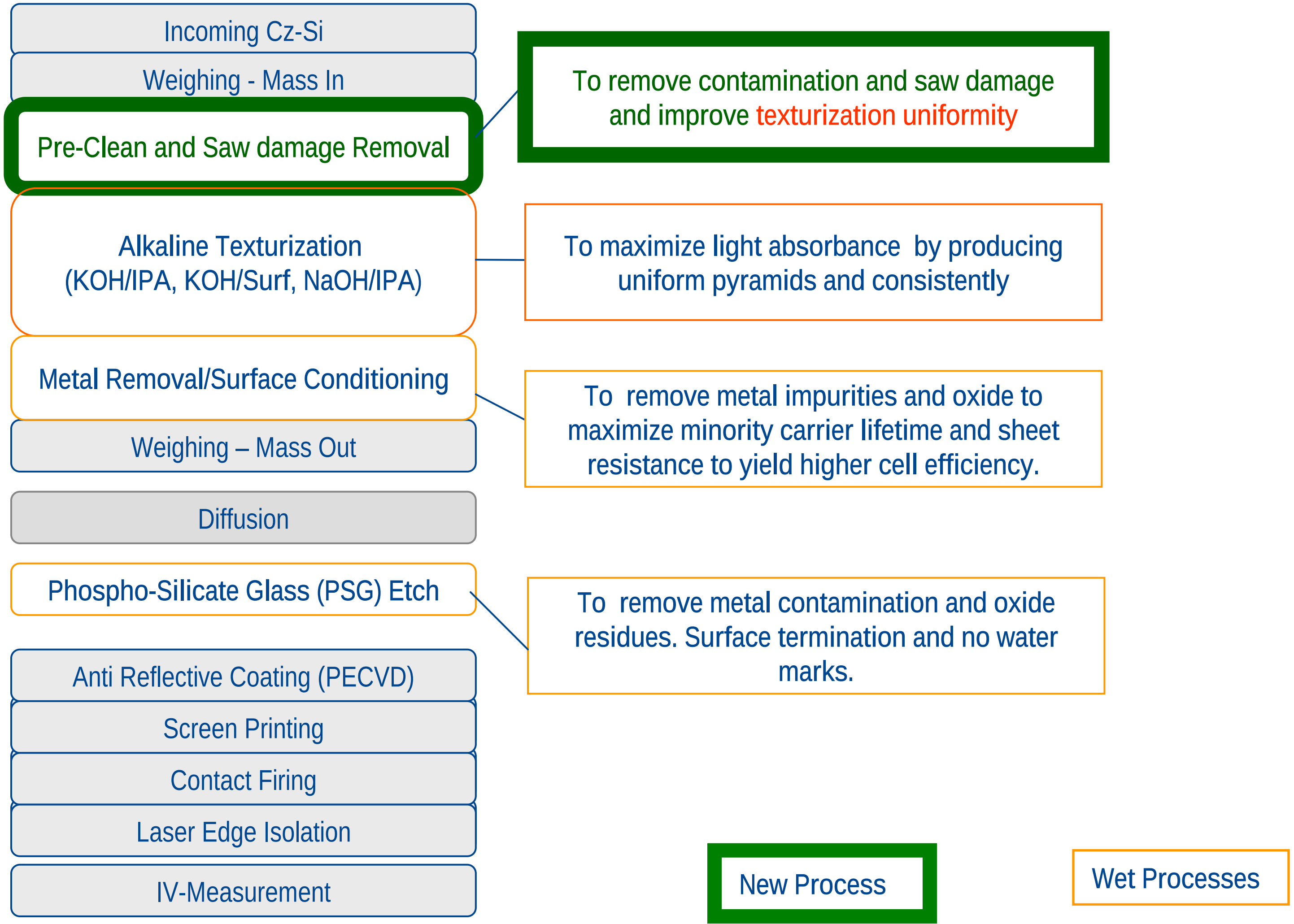
Outline

- Introduction
- Experimental
- Results
  - Impact of Surface Contamination and Importance of Pre-cleaning
  - Surface Analysis
  - IPA Replacement
  - Concentration Control
  - COO Modeling
- Summary

Introduction

- Effective light absorption at pyramidal surfaces of c-Si solar wafers texturized with alkaline solutions is commonly applied in the PV industry
- Small pyramid dimensions resulting in low surface reflectance is normally considered a key factor for enhancing solar cell efficiency
- With introduction of HIT (heterojunction intrinsic thin-layer) technologies, increased densities of the peak and valley with decreased pyramid size have been found to be detrimental to solar cell performance
- Optimization of pyramidal textures with appropriate surface morphology is desired for advanced solar cell development
- The effect of cleaning pre- and post-texture treatment on alkaline texturization and cell efficiency needs to be addressed

Basic Process Flow and POR



Incoming Cz-Si

Weighing - Mass In

Pre-Clean and Saw damage Removal

Alkaline Texturization
(KOH/IPA, KOH/Surf, NaOH/IPA)

Metal Removal/Surface Conditioning

Weighing – Mass Out

Diffusion

Phospho-Silicate Glass (PSG) Etch

Anti Reflective Coating (PECVD)

Screen Printing

Contact Firing

Laser Edge Isolation

IV-Measurement

To remove contamination and saw damage and improve texturization uniformity

To maximize light absorbance by producing uniform pyramids and consistently

To remove metal impurities and oxide to maximize minority carrier lifetime and sheet resistance to yield higher cell efficiency.

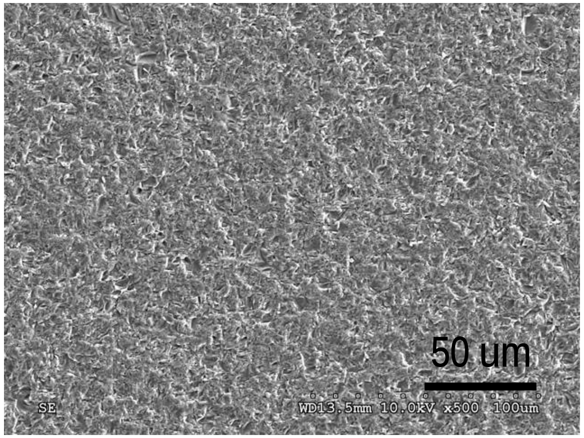
To remove metal contamination and oxide residues. Surface termination and no water marks.

New Process

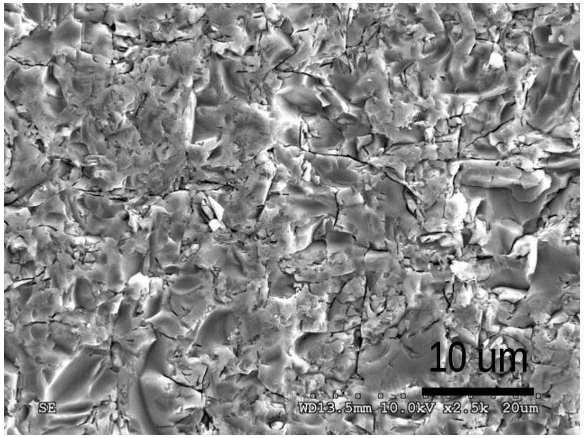
Wet Processes

Typical Surface Morphologies

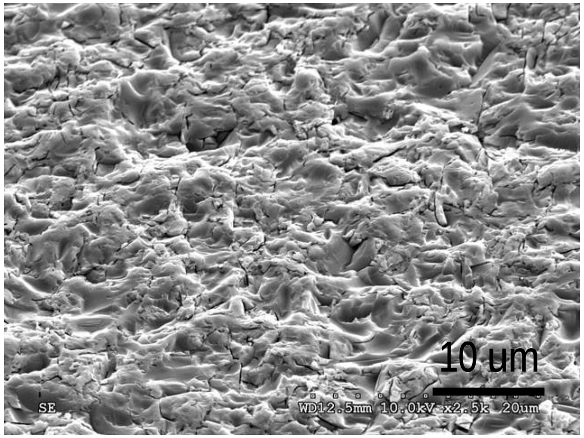
(Tests Performed in Akrion Systems Tool)



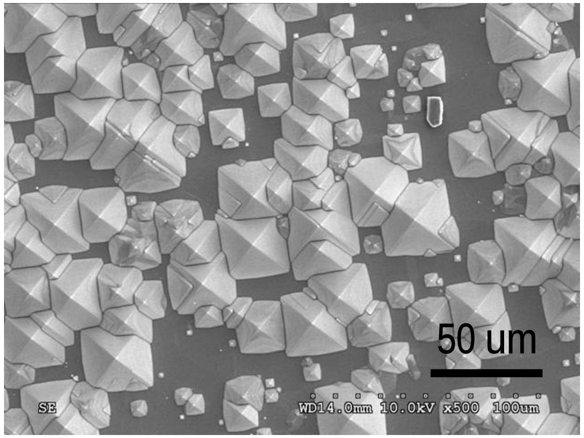
As-cut Surface (topdown 500X)



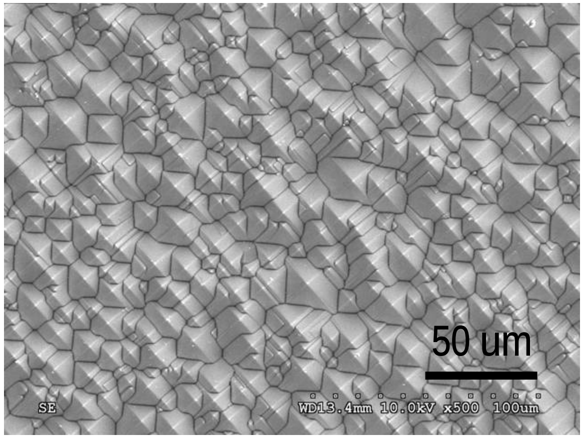
As-cut Surface (topdown 2500X)



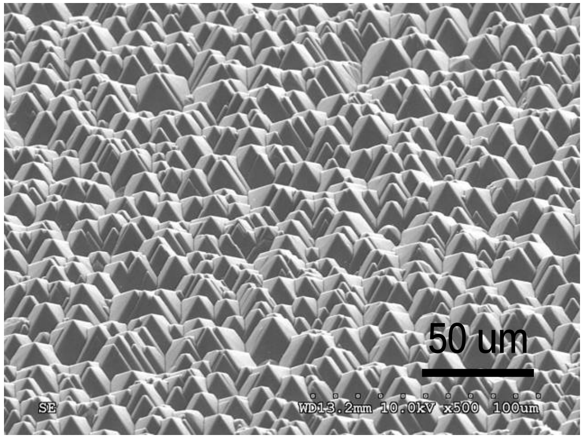
As-cut Surface (45° tilted 2500X)



Partially Textured Surface (topdown 500X)



Fully Textured Surface (topdown 500X)



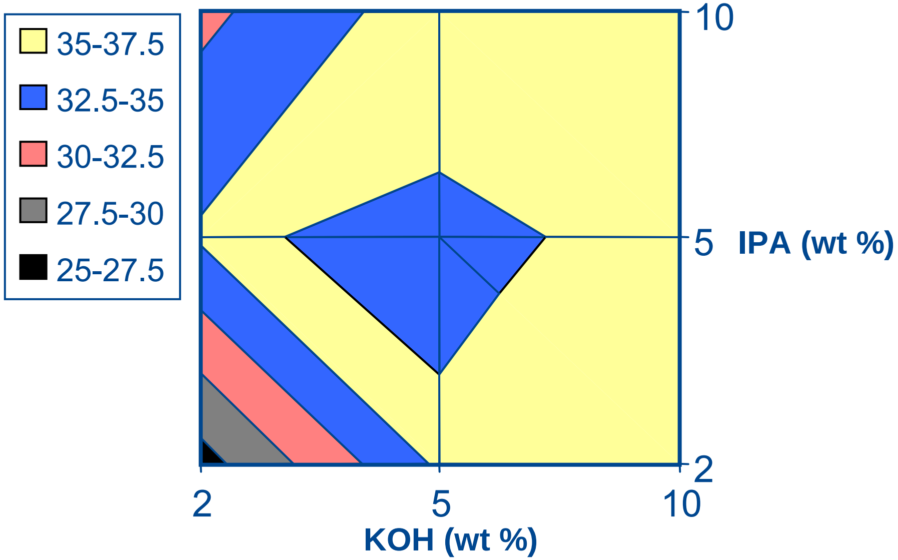
Fully Textured Surface (60° tilted 500X)

Basic Characterization

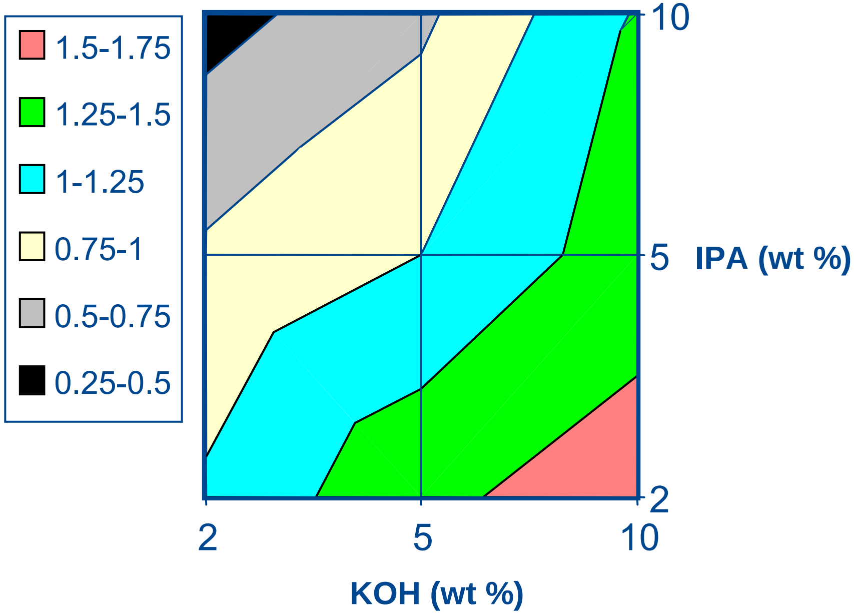
Texturization Characterization

Surface Preparation Techniques

Silicon Etch Rate vs. KOH/IPA Concentration



Minimum Reflectance (%)
(from 400nm to 700nm wavelength)



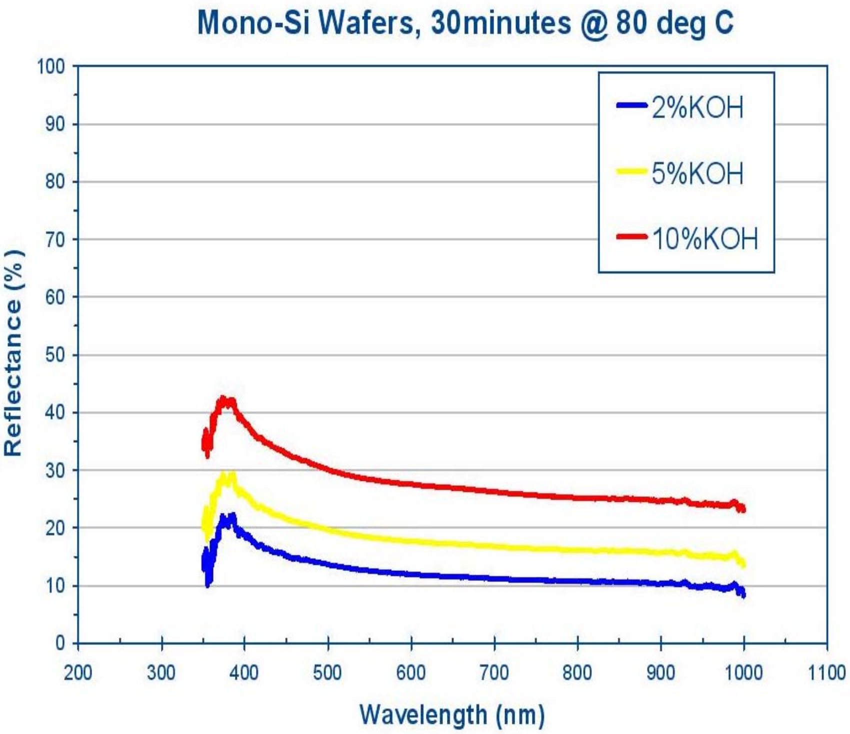
Si Etch Rate (µm/minute)

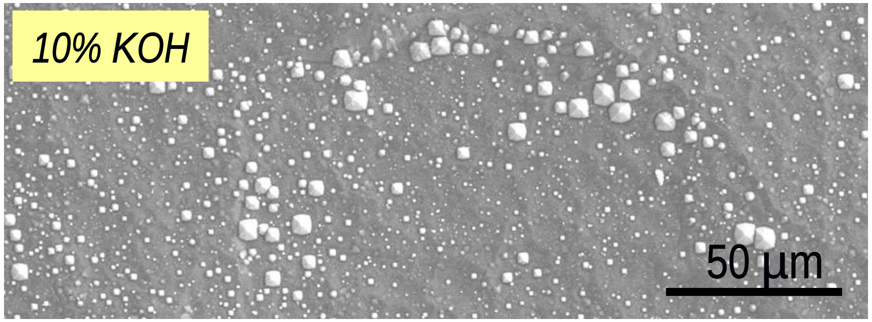
Reflectance and Etch Rate ↑ as KOH ↑, while Etch Rate ↓ as IPA ↑

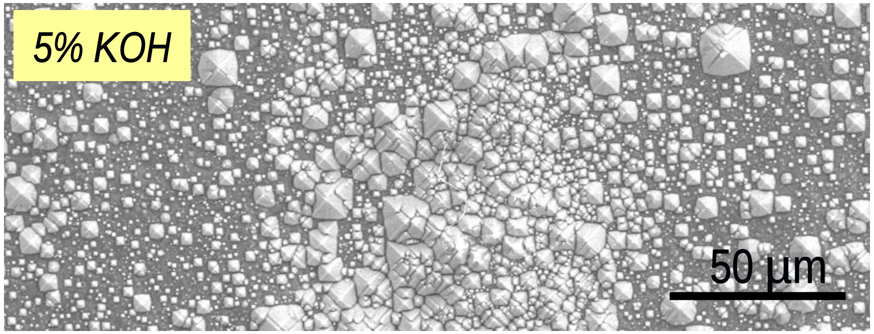
To minimize Si loss, it is preferable to decrease KOH but increase IPA

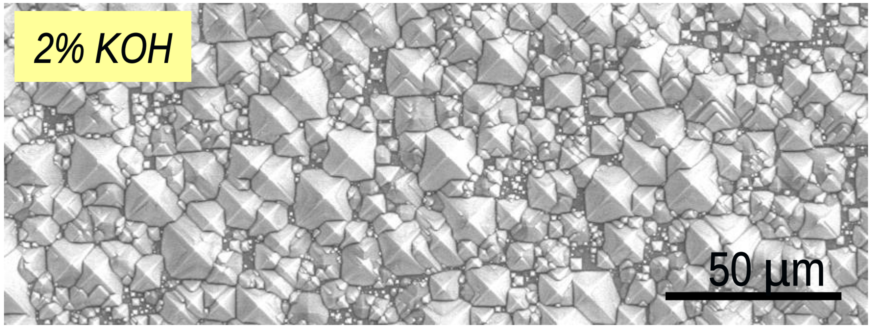
KOH Concentration Effects

(KOH Solution Only)



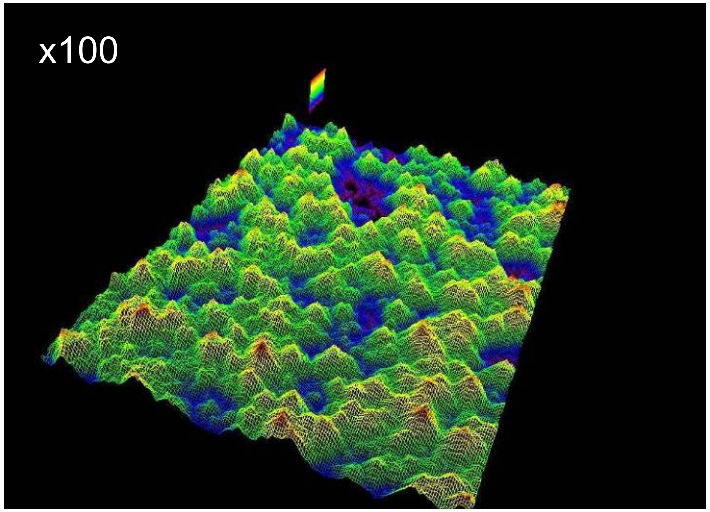






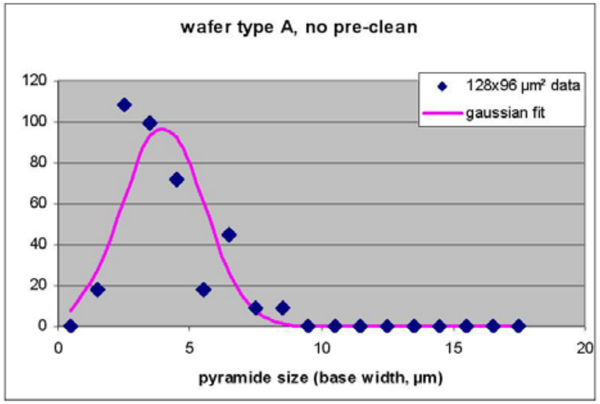
- High KOH% reduces pyramid sizes/densities and therefore surface reflectance
- Without IPA, pyramid distribution is not uniform

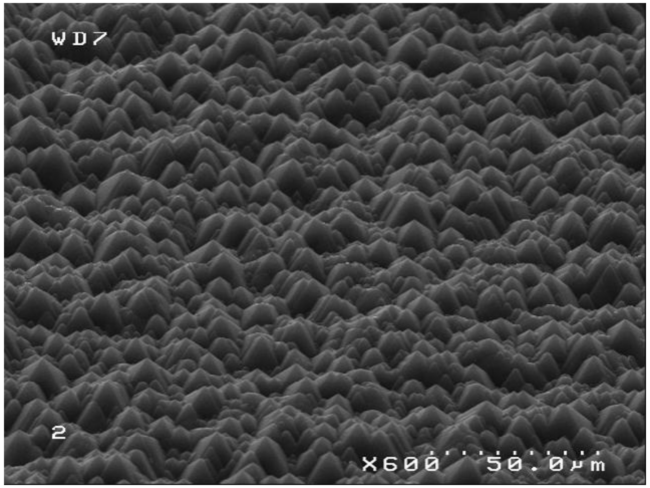
Wafer Type A, No Pre-clean

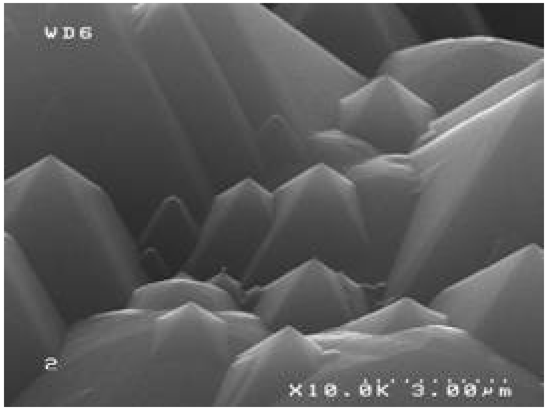


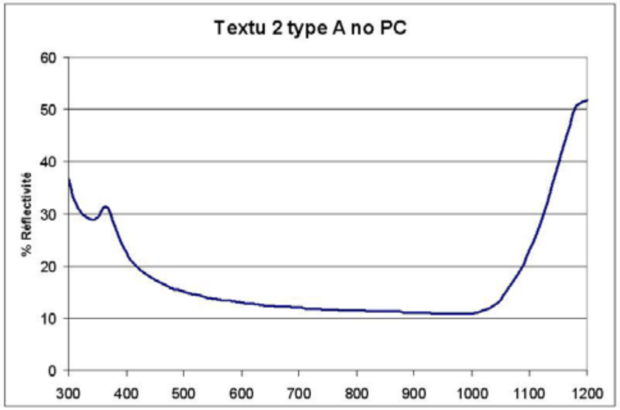
Etch rate: 0.25 µm/min/side
Reff @ 950nm: 10.95%
Rw 300-950: 13.66%
Rw 300-1200: 15.58%
Pyramid base width:
- -min. = 1.95 µm
- -max. = 8.14 µm
- -ave. = 3.98 µm
- -sigma = 1.55 µm

Pyramid density: 3.14e+06 /cm²

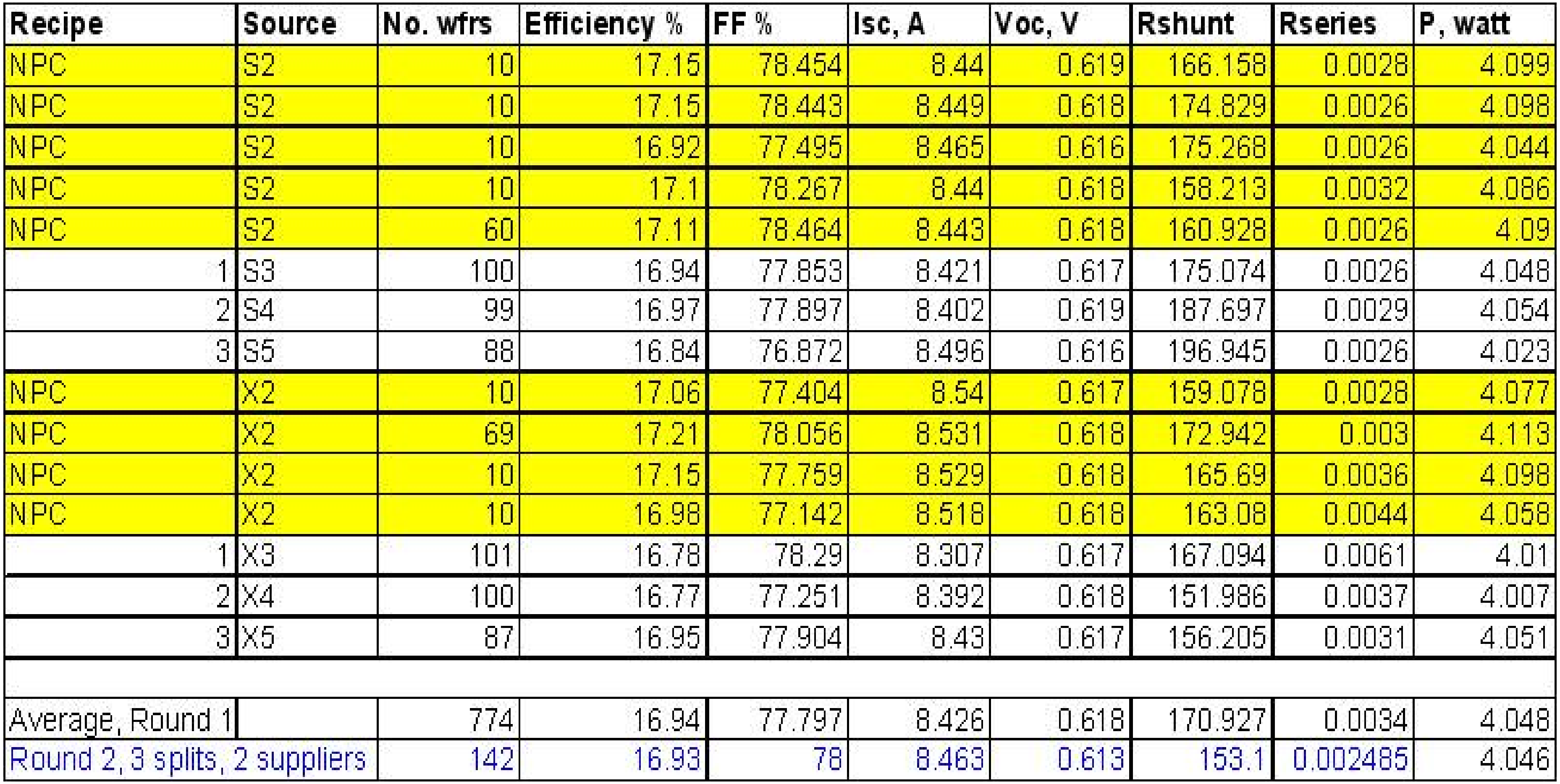








Efficiency Data

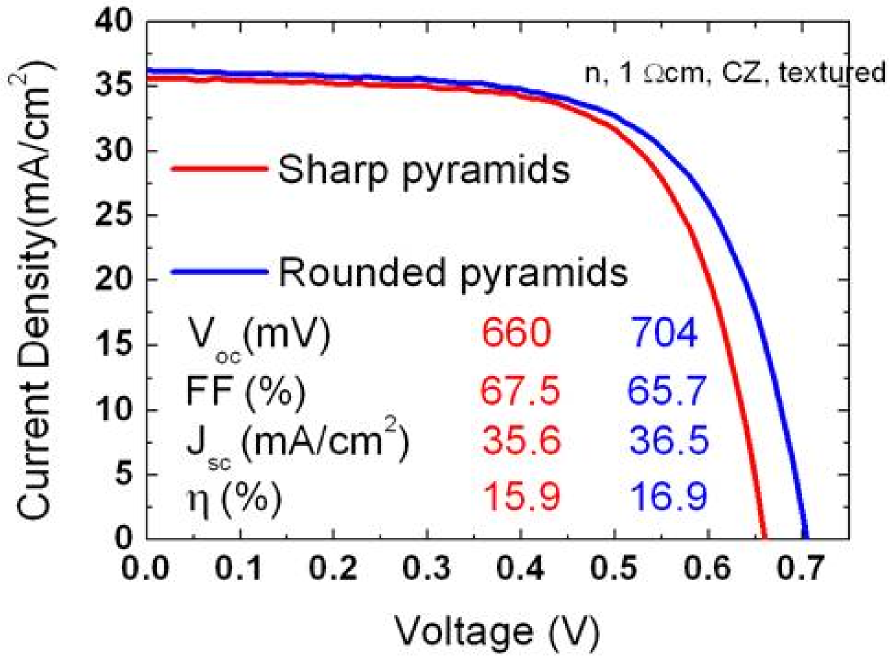


Recipe	Source	No. wfrs	Efficiency %	FF %	Isc, A	Voc, V	Rshunt	Rseries	P, watt
NPC	S2	10	17.15	78.454	8.44	0.619	166.158	0.0028	4.099
NPC	S2	10	17.15	78.443	8.449	0.618	174.829	0.0026	4.098
NPC	S2	10	16.92	77.495	8.465	0.616	175.268	0.0026	4.044
NPC	S2	10	17.1	78.267	8.44	0.618	158.213	0.0032	4.086
NPC	S2	60	17.11	78.464	8.443	0.618	160.928	0.0026	4.09
1	S3	100	16.94	77.853	8.421	0.617	175.074	0.0026	4.048
2	S4	99	16.97	77.897	8.402	0.619	187.697	0.0029	4.054
3	S5	88	16.84	76.872	8.496	0.616	196.945	0.0026	4.023
NPC	X2	10	17.06	77.404	8.54	0.617	159.078	0.0028	4.077
NPC	X2	69	17.21	78.056	8.531	0.618	172.942	0.003	4.113
NPC	X2	10	17.15	77.759	8.529	0.618	165.69	0.0036	4.098
NPC	X2	10	16.98	77.142	8.518	0.618	163.08	0.0044	4.058
1	X3	101	16.78	78.29	8.307	0.617	167.094	0.0061	4.01
2	X4	100	16.77	77.251	8.392	0.618	151.986	0.0037	4.007
3	X5	87	16.95	77.904	8.43	0.617	156.205	0.0031	4.051
Average, Round 1		774	16.94	77.797	8.426	0.618	170.927	0.0034	4.048
Round 2, 3 splits, 2 suppliers		142	16.93	78	8.463	0.613	153.1	0.002485	4.046

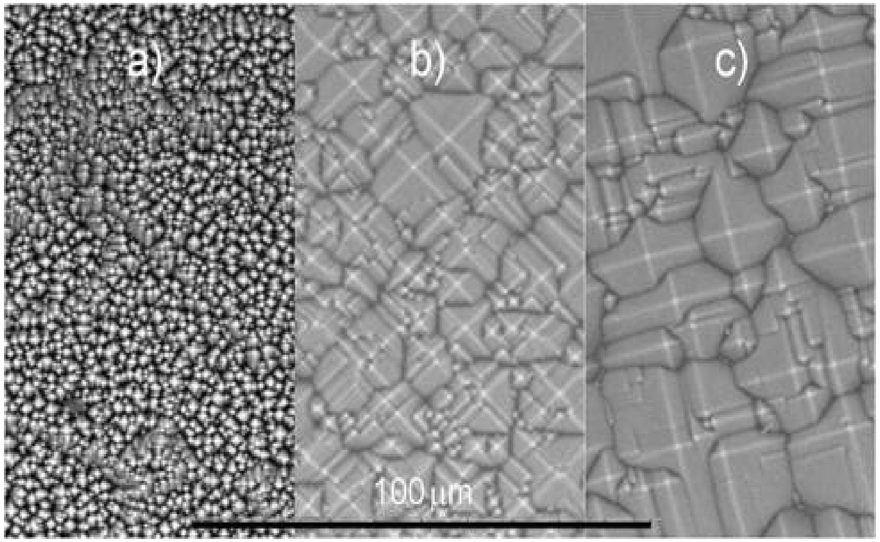
FF and Isc are good and show stable process

Voc may need to increase and indicate material bulk or surface quality issues

Pyramid Sizes and Distribution



IV curves of final solar cells on large pyramids, with or without post texturization chemical polishing



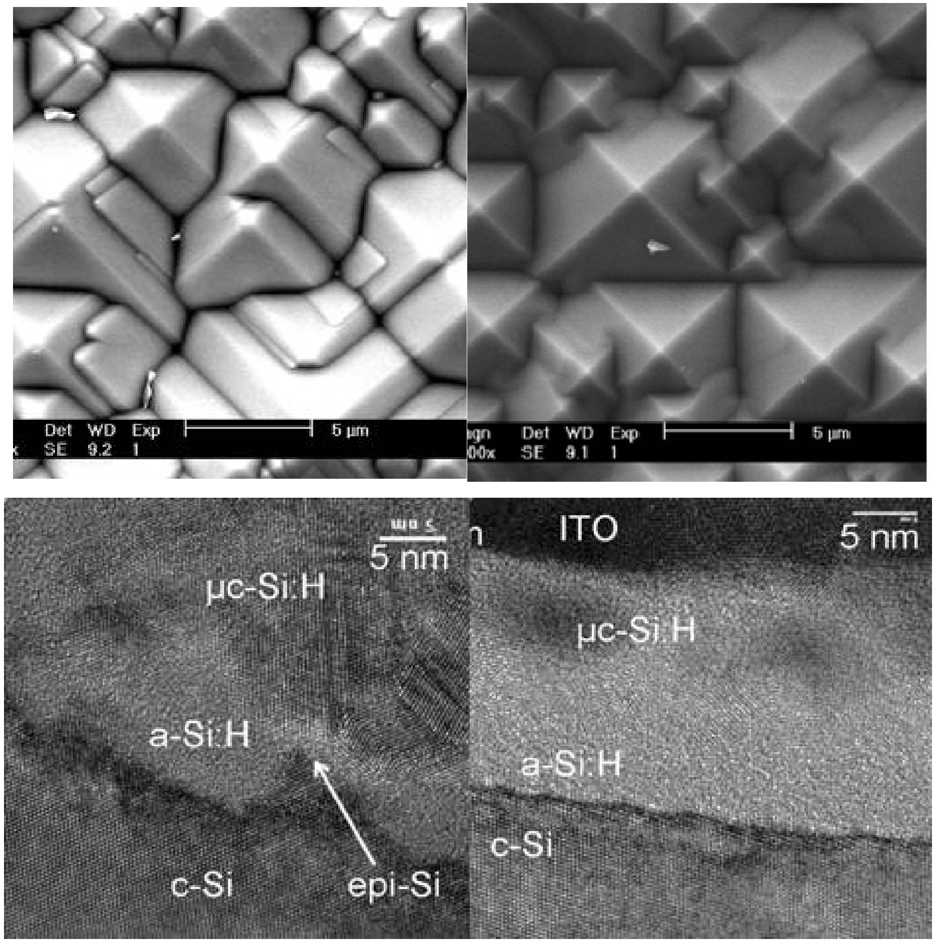
Textured wafers with different average pyramid sizes:

a) 1-3 µm height pyramids
b) 5-15 µm height pyramids
c) 10-25 µm height pyramids

Small pyramids present a challenge to film deposition for HIT cells: Local epitaxial growth and chemical contamination potential

L. Fesquet, et al, IEEE PVSEC 34

High Efficiency Cells and Effect of Surface Preparation



Before Final Clean

After Final Clean

Before Final Clean

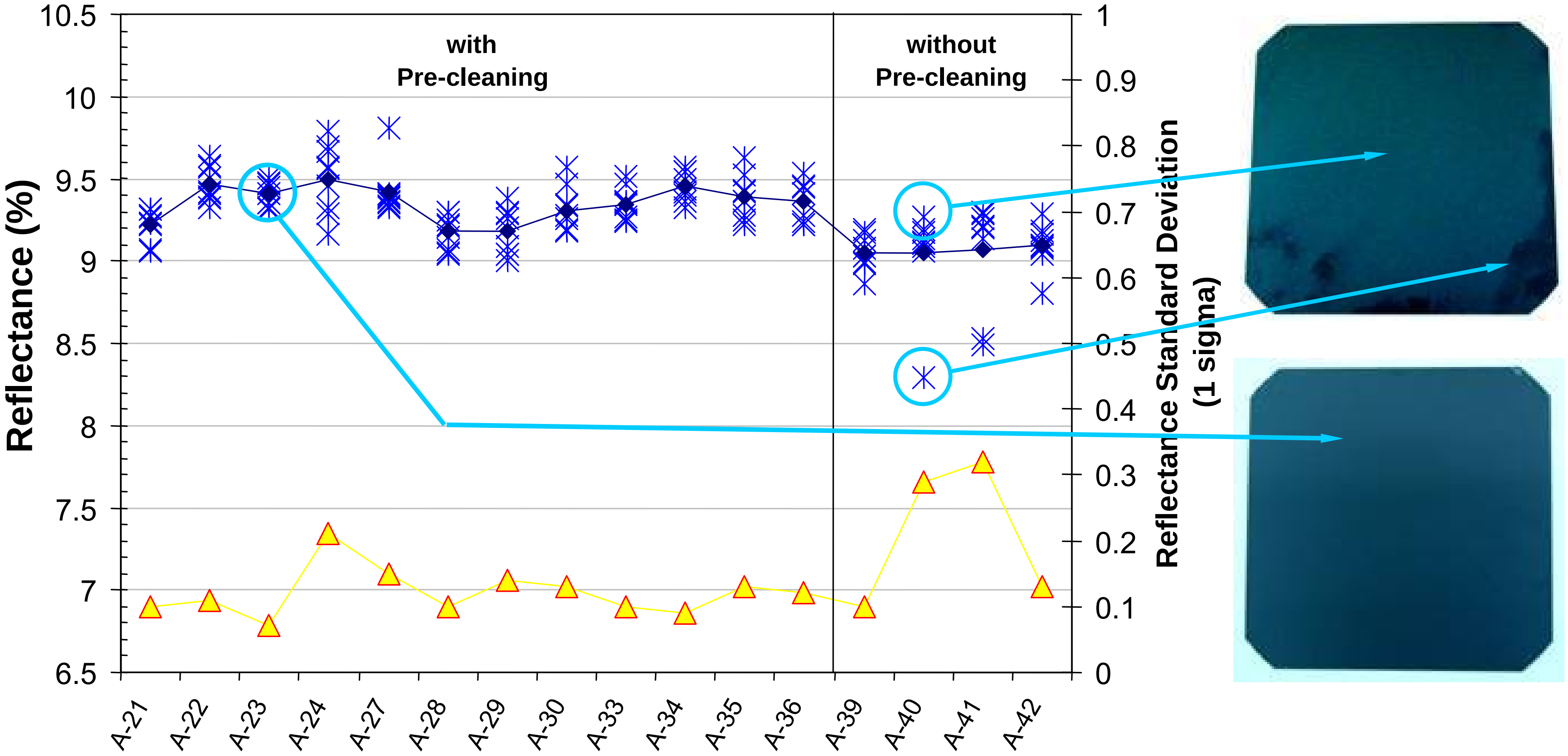
After Final Clean

SEM picture of textured c-Si wafer (5-15 µm pyramids) a) before, and b) after post-texturization chemical polishing

(L. Fesquet, et al, IEEE PVSEC 34)

Importance of Pre-Cleaning

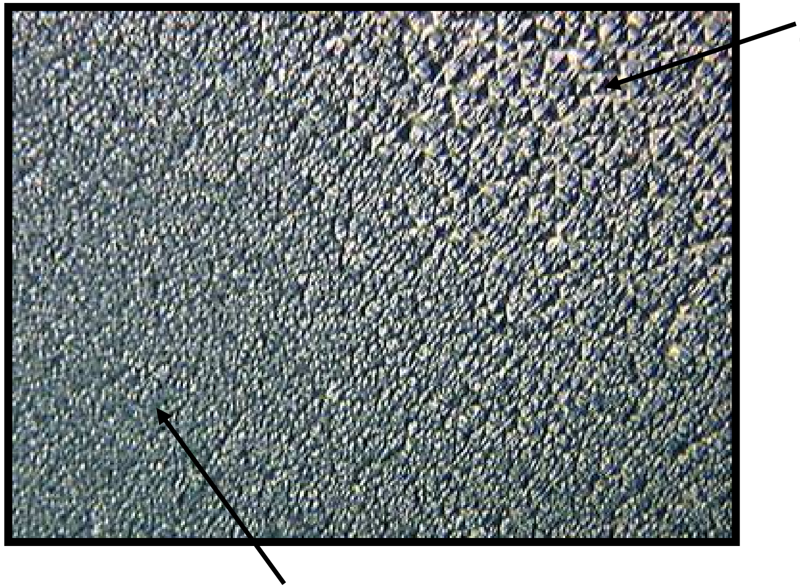
Reflectance Non-Uniformity by Surface Contamination (1)



Pre-cleaning can reduce reflectance non-uniformity by removing surface contaminants

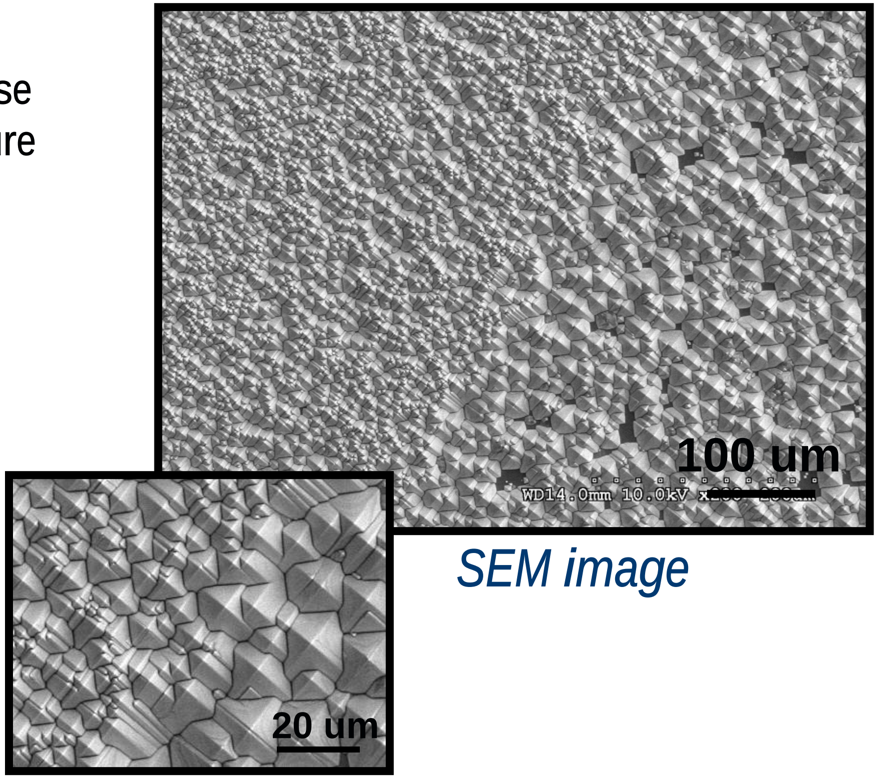
Texture Morphology of Contaminated Area (1)

Optical image (200X)



Coarse Texture

Fine Texture



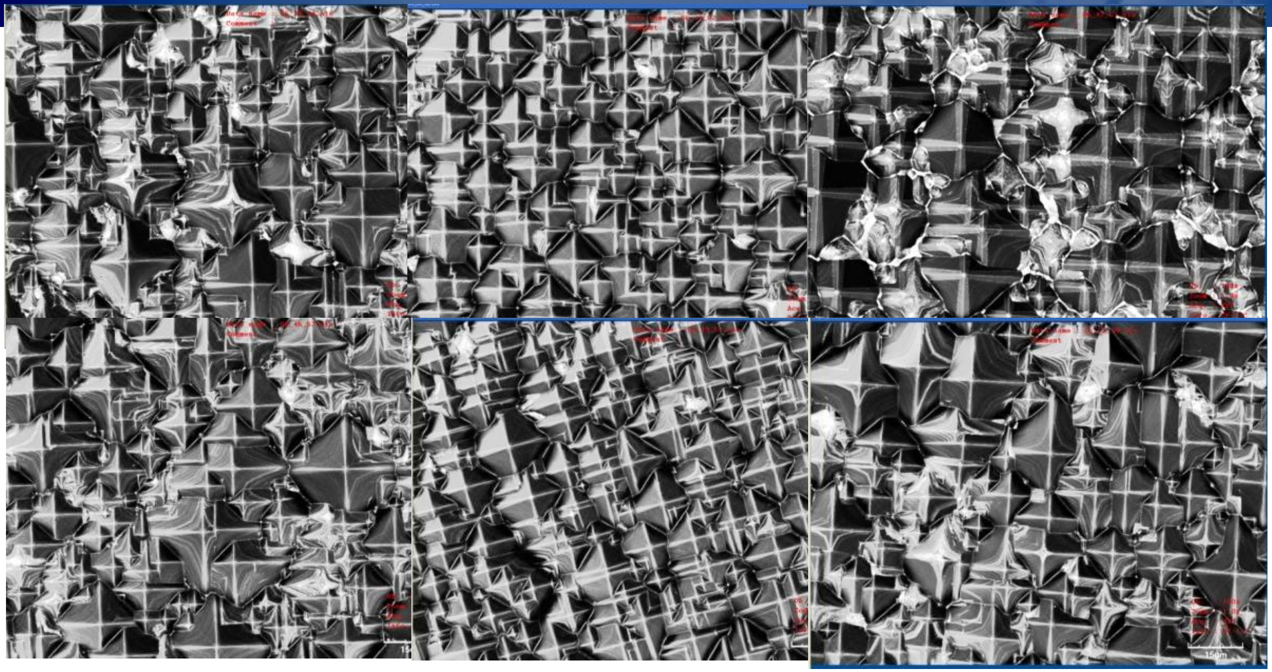
SEM image

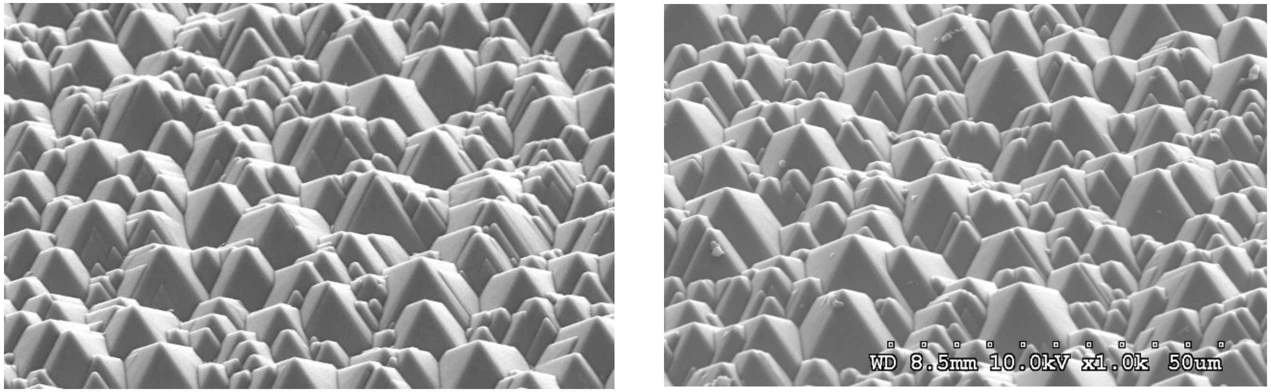
Contaminated areas induce smaller pyramids

Areas with smaller pyramids show lower reflectance

Texturization Analysis

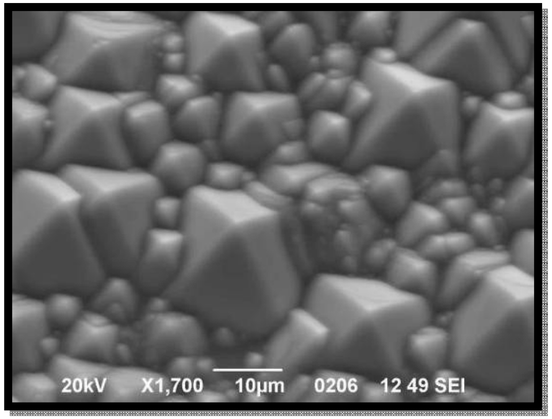
Confocal 3D Laser vs. SEM Analysis





- Critical and careful examination is still required
- Confocal is a quick and easier tool than SEM. Yet, it does not reveal the whole picture
- Sophisticated image analysis is typically needed

Wafer Texturing Comparison

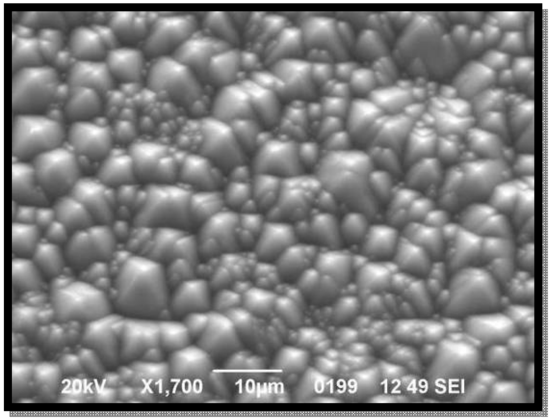


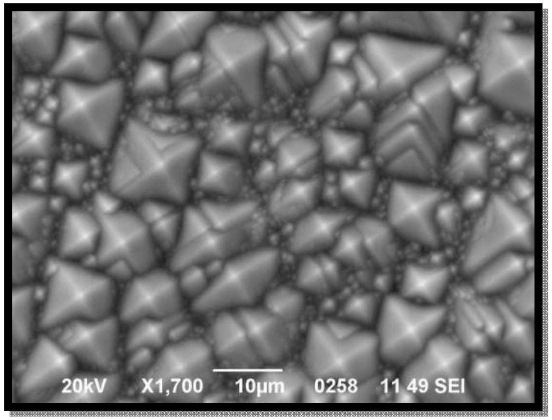
Supplier C

~10 µm texture
- Moderate Uniformity
- No Non-Etched Areas

Supplier-A

~ ≤10 µm texture
- High Uniformity
- No Non-Etched Areas





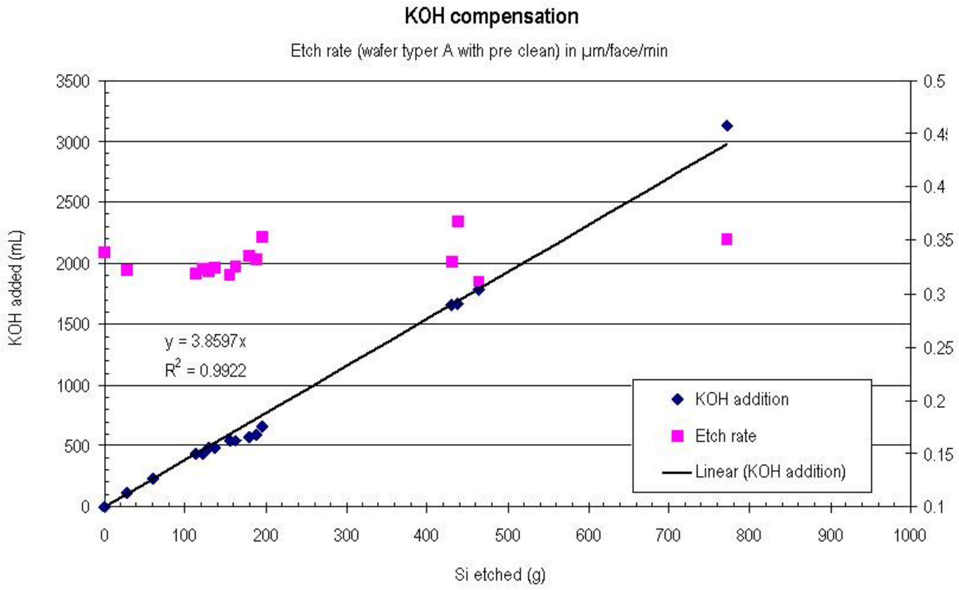
Supplier-B

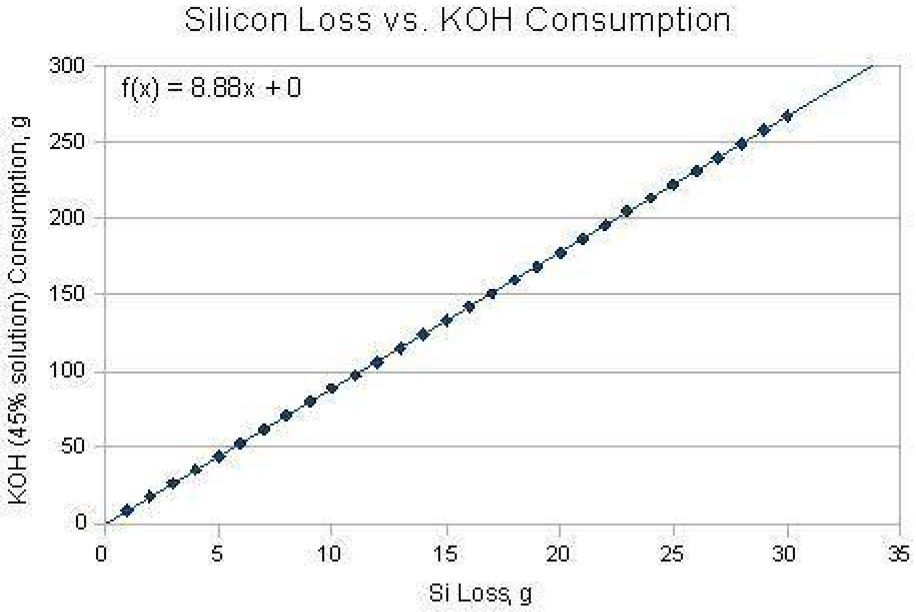
~≤10 µm texture
- Moderate Uniformity
- No Non-Etched Areas

Small variation in texturization patterns but all meet post-processing carrier lifetime requirements

Process Stability vs. Si Content

$Si + 2KOH + H_2O \rightarrow K_2SiO_3 + 2H_2$

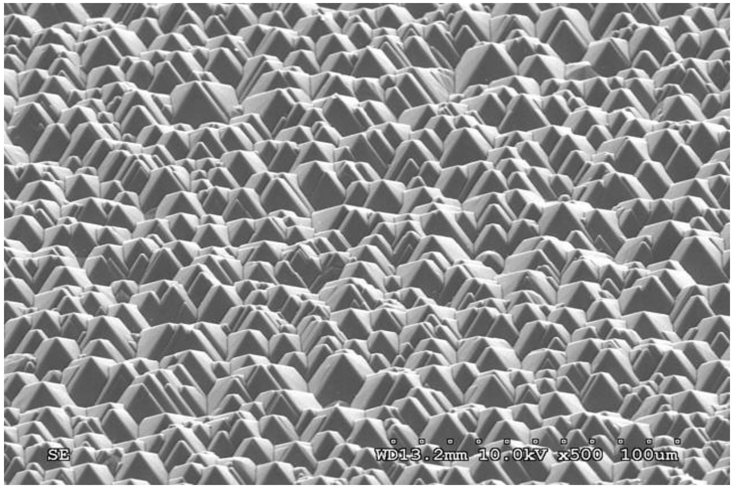


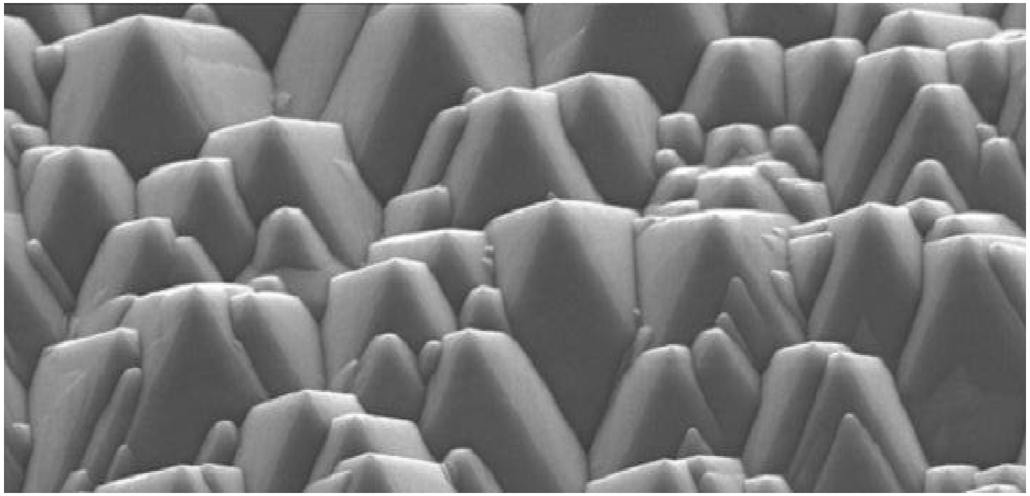


Silicates concentration in the bath must be controlled to obtain a stable ER i.e. feed/bleed and chemicals concentration control

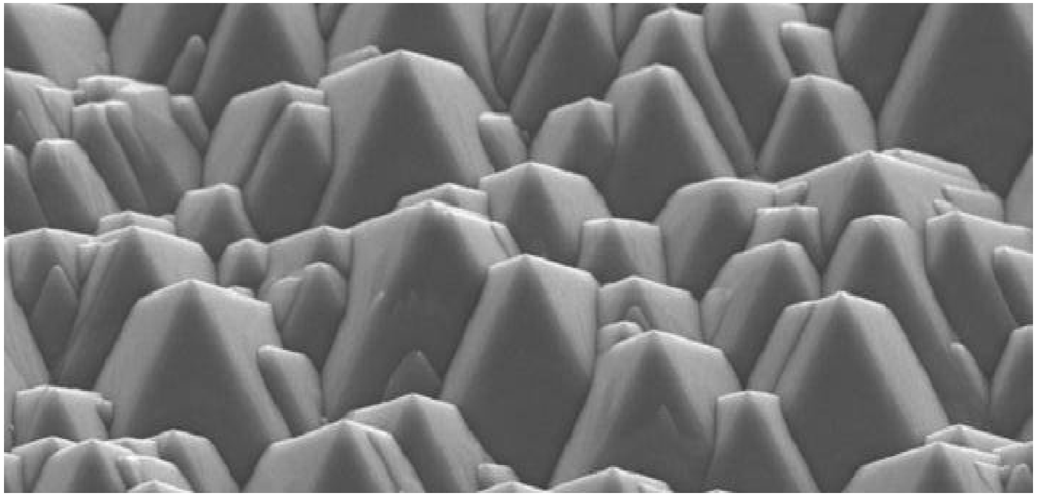
IPA Replacement

IPA Replacement (SCD2000)





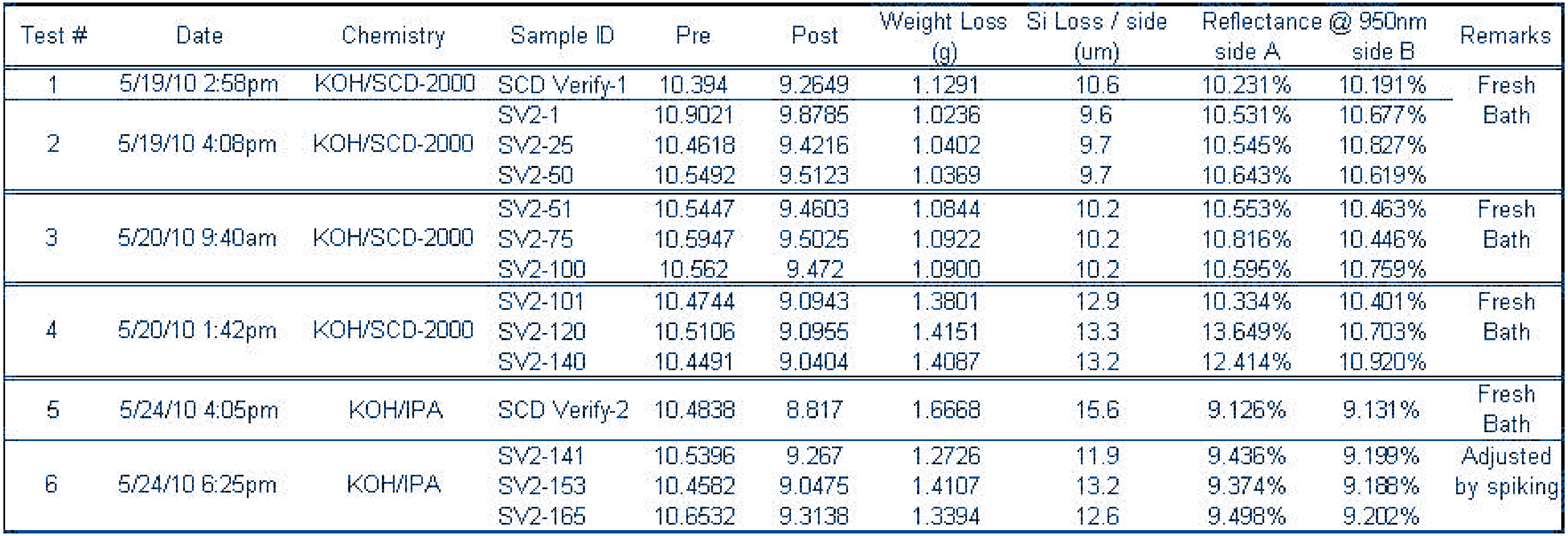
KOH/IPA



KOH/Surfactant

IPA Replacement (SCD2000)

Efficiency data being generated



Test #	Date	Chemistry	Sample ID	Pre	Post	Weight Loss (g)	Si Loss / side (um)	Reflectance @ 950nm		Remarks
								side A	side B	
1	5/19/10 2:58pm	KOH/SCD-2000	SCD Verify-1	10.394	9.2649	1.1291	10.6	10.231%	10.191%	Fresh Bath
2	5/19/10 4:08pm	KOH/SCD-2000	SV2-1	10.9021	9.8785	1.0236	9.6	10.531%	10.677%	
			SV2-25	10.4618	9.4216	1.0402	9.7	10.545%	10.827%	
			SV2-50	10.5492	9.5123	1.0369	9.7	10.643%	10.619%	
3	5/20/10 9:40am	KOH/SCD-2000	SV2-51	10.5447	9.4603	1.0844	10.2	10.553%	10.463%	Fresh Bath
			SV2-75	10.5947	9.5025	1.0922	10.2	10.816%	10.446%	
			SV2-100	10.562	9.472	1.0900	10.2	10.595%	10.759%	
4	5/20/10 1:42pm	KOH/SCD-2000	SV2-101	10.4744	9.0943	1.3801	12.9	10.334%	10.401%	Fresh Bath
			SV2-120	10.5106	9.0955	1.4151	13.3	13.649%	10.703%	
			SV2-140	10.4491	9.0404	1.4087	13.2	12.414%	10.920%	
5	5/24/10 4:05pm	KOH/IPA	SCD Verify-2	10.4838	8.817	1.6668	15.6	9.126%	9.131%	Fresh Bath
6	5/24/10 6:25pm	KOH/IPA	SV2-141	10.5396	9.267	1.2726	11.9	9.436%	9.199%	Adjusted by spiking
			SV2-153	10.4582	9.0475	1.4107	13.2	9.374%	9.188%	
			SV2-165	10.6532	9.3138	1.3394	12.6	9.498%	9.202%	

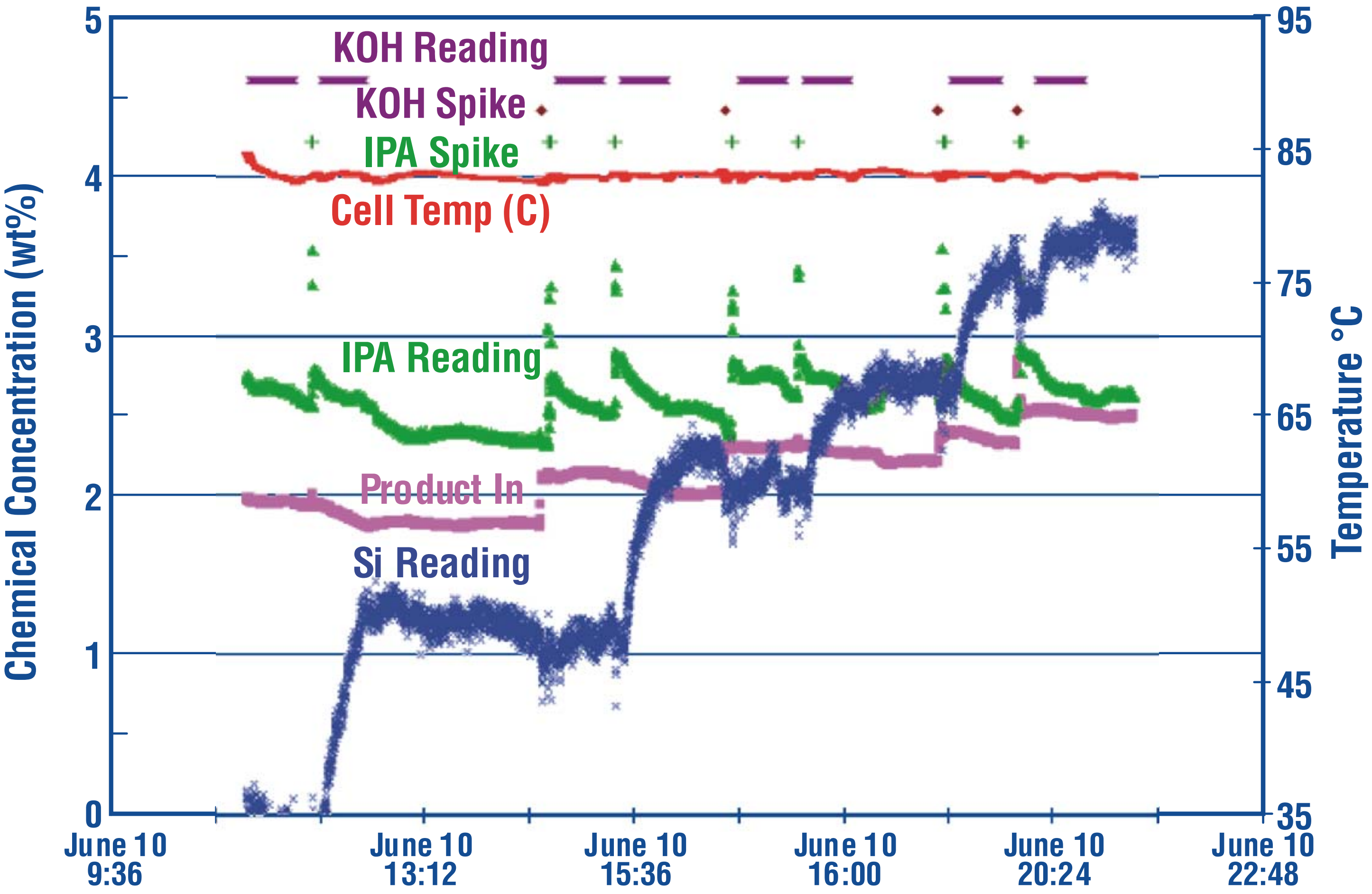
- Reflectance is typically higher in surfactant compared to BKM
- Encouraging results but uniformity needs to be improved (scatter between small and large pyramids)
- Effect of surfactant on etch mechanism yet to be understood. Pyramids are not as sharp compared to BKM results

Chemical Concentration Control for Solar Applications

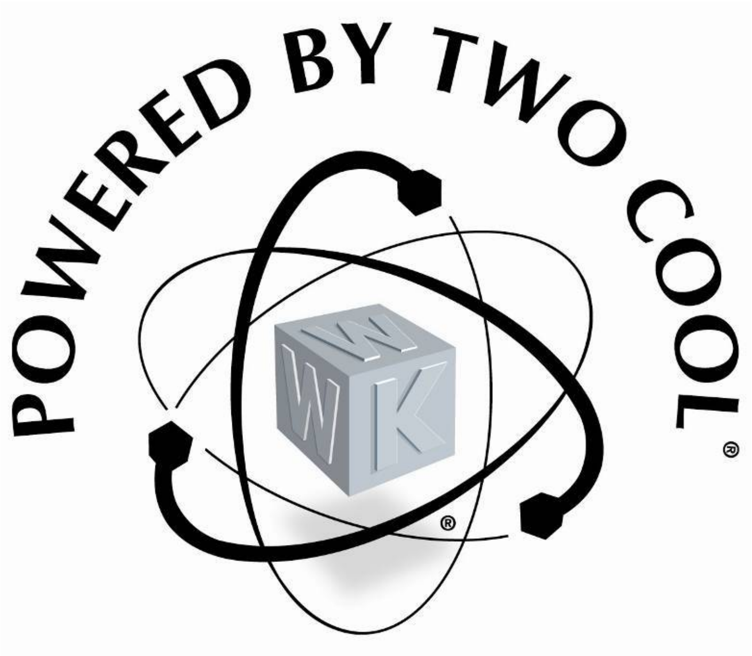
Akrion Systems' ICE-1™ Benefits

- ICE technology accurately predicts the concentration of chemicals and produces the desired process results e.g. texturization pattern
- The technology is effective in reducing the COO and overall cost of manufacturing by extending the bath lives
- The technology extends up-time and overall utilization of the tool and hence lowers cost of manufacturing
- The technology reduces the time for field installation by eliminating the time and resources required to dial-in the right chemicals' concentration over many hours and days. With a closed loop concentration control, this process will no longer require many iterations and tedious work until the results are achieved
- The technology significantly reduces rework and wafer mis-processing

ICE for Solar (NIR Sensor)



COO Modeling



Cost of Ownership Algorithm

$$COO = \frac{F\$ + (R\$ + Y\$)}{L \times T \times Y \times U}$$

F$ = Fixed Costs

R$ = Recurring Costs

Y$ = Yield Costs

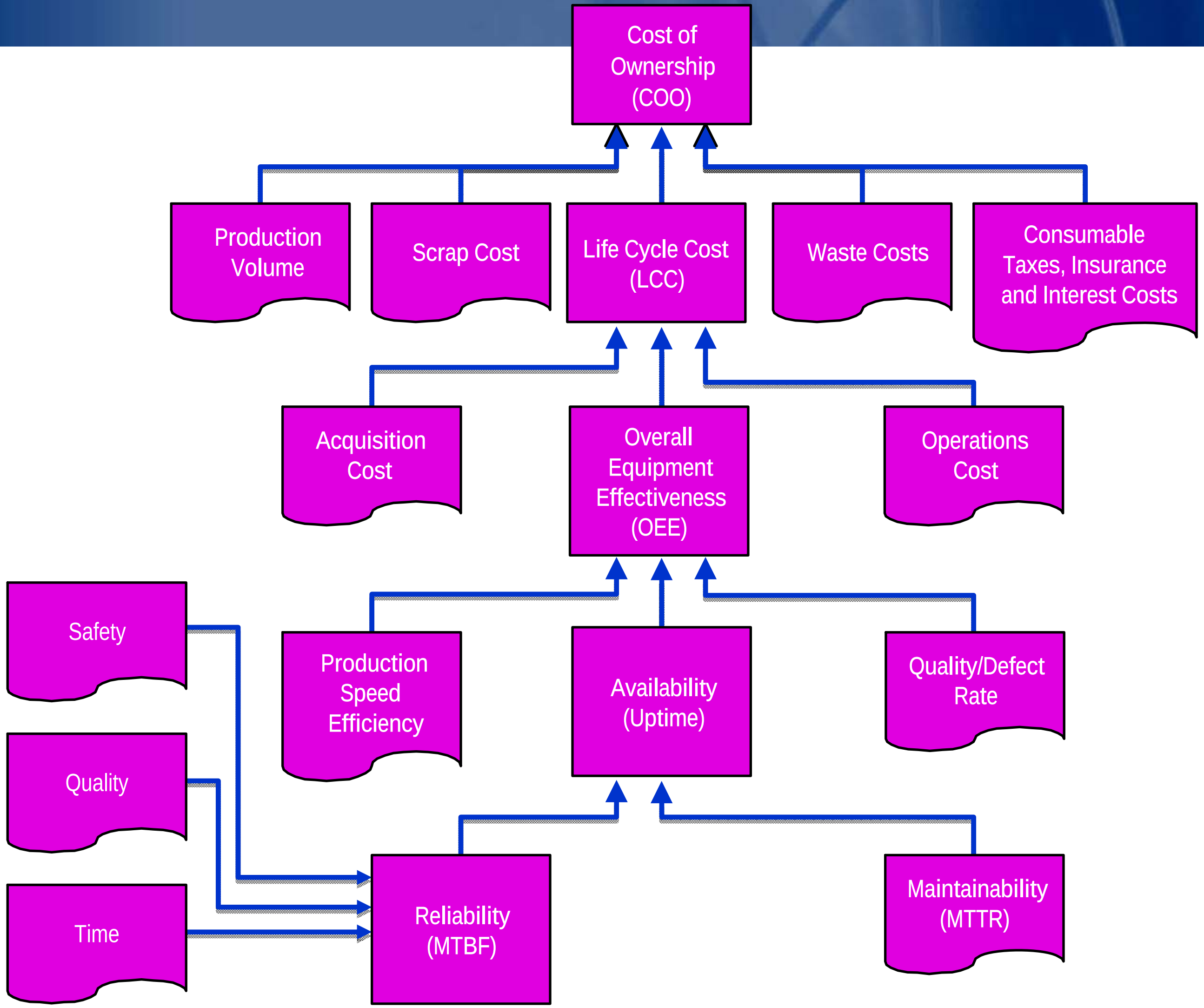
L = Tool Life

T = Throughput

Y = Composite Yield

U = Utilization

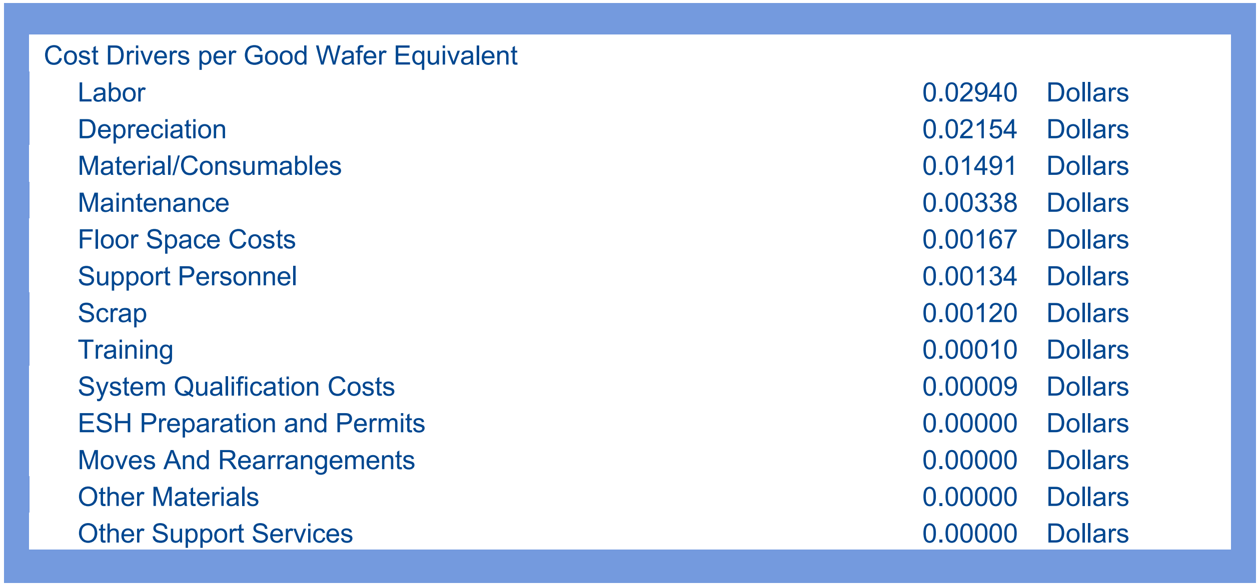
Equipment Performance Metrics



Courtesy of
Dr. Vallabh Dhudshia,
Former Texas
Instruments Fellow

Pareto of Cost Drivers

- Top 3 cost drivers account for 90% of COO
- Examine the cost sensitivities to input parameters that drive Labor (40%), Depreciation (30%), and Material (20%) costs

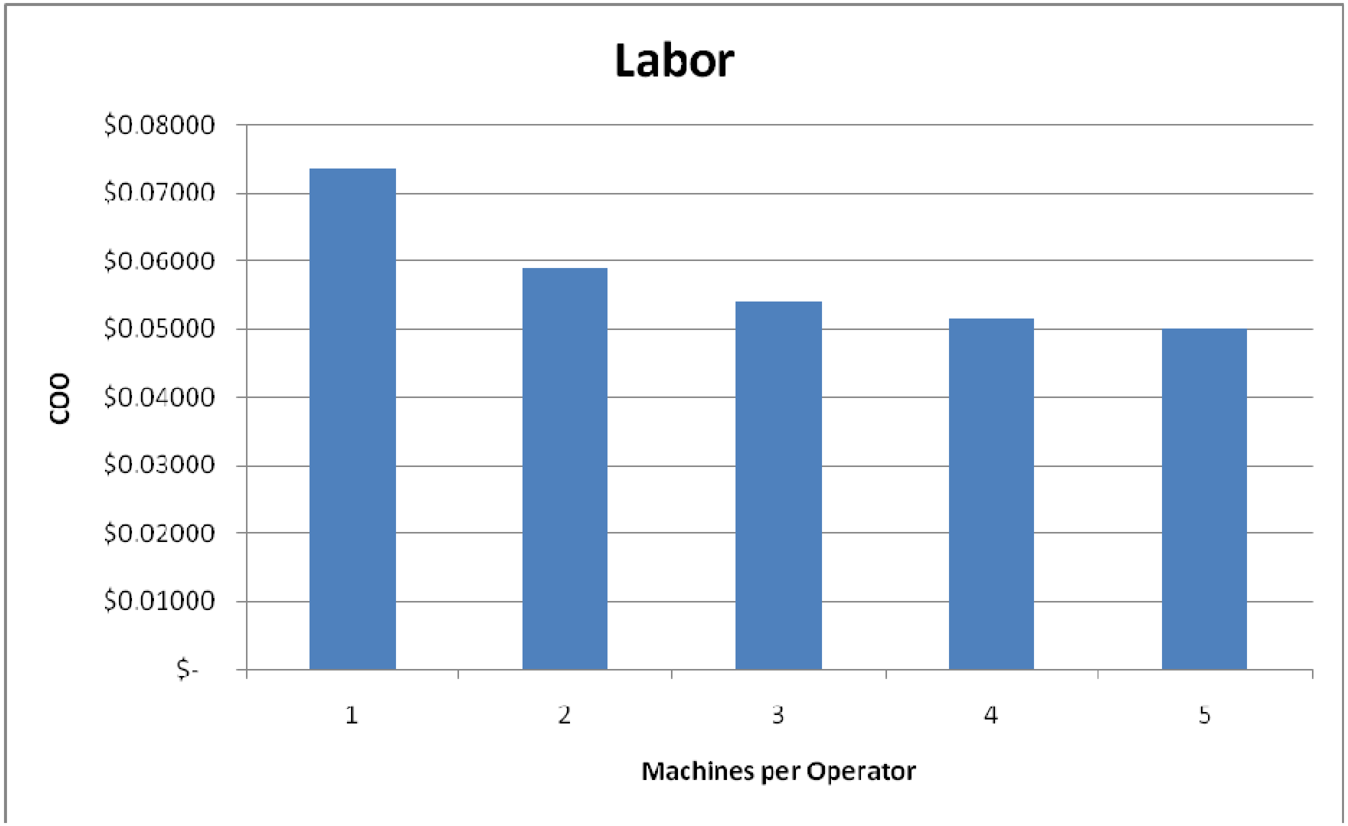


Cost Drivers per Good Wafer Equivalent		
Labor	0.02940	Dollars
Depreciation	0.02154	Dollars
Material/Consumables	0.01491	Dollars
Maintenance	0.00338	Dollars
Floor Space Costs	0.00167	Dollars
Support Personnel	0.00134	Dollars
Scrap	0.00120	Dollars
Training	0.00010	Dollars
System Qualification Costs	0.00009	Dollars
ESH Preparation and Permits	0.00000	Dollars
Moves And Rearrangements	0.00000	Dollars
Other Materials	0.00000	Dollars
Other Support Services	0.00000	Dollars

Labor Sensitivity

- Labor content represents 40% of the COO for these integrated process steps
- Labor is defined as direct operator labor
    - Model is based on one operator overseeing one machine
- Since these are highly automated machines with sufficient throughput to support a 30 MW line, it is not likely that the factory would be significantly larger in order to allow for further amortization of labor content
- However, the next slide does examine COO sensitivity to labor content should such opportunities present themselves

Labor Sensitivity (continued)

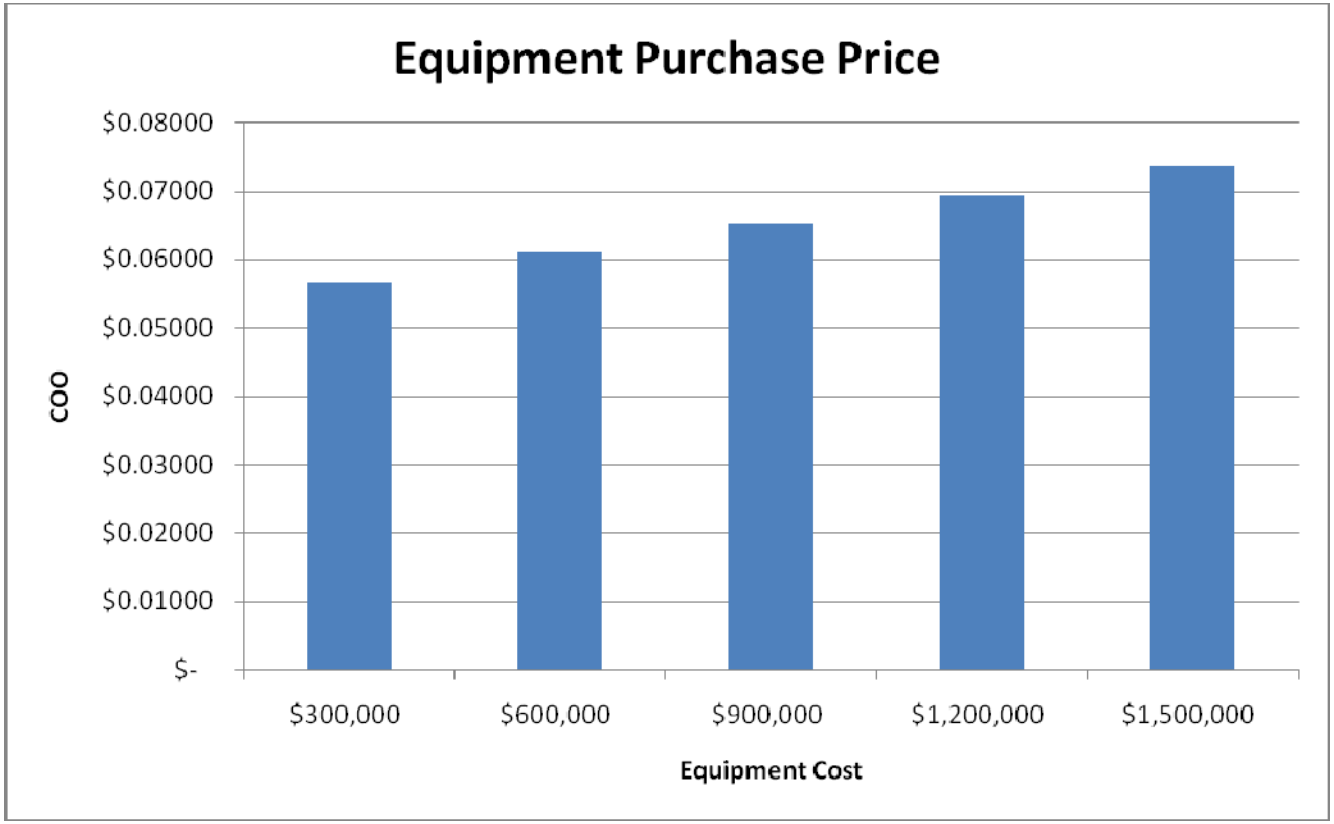


Move from 1-2 machines per operator decreases COO by 20%

Depreciation Sensitivity

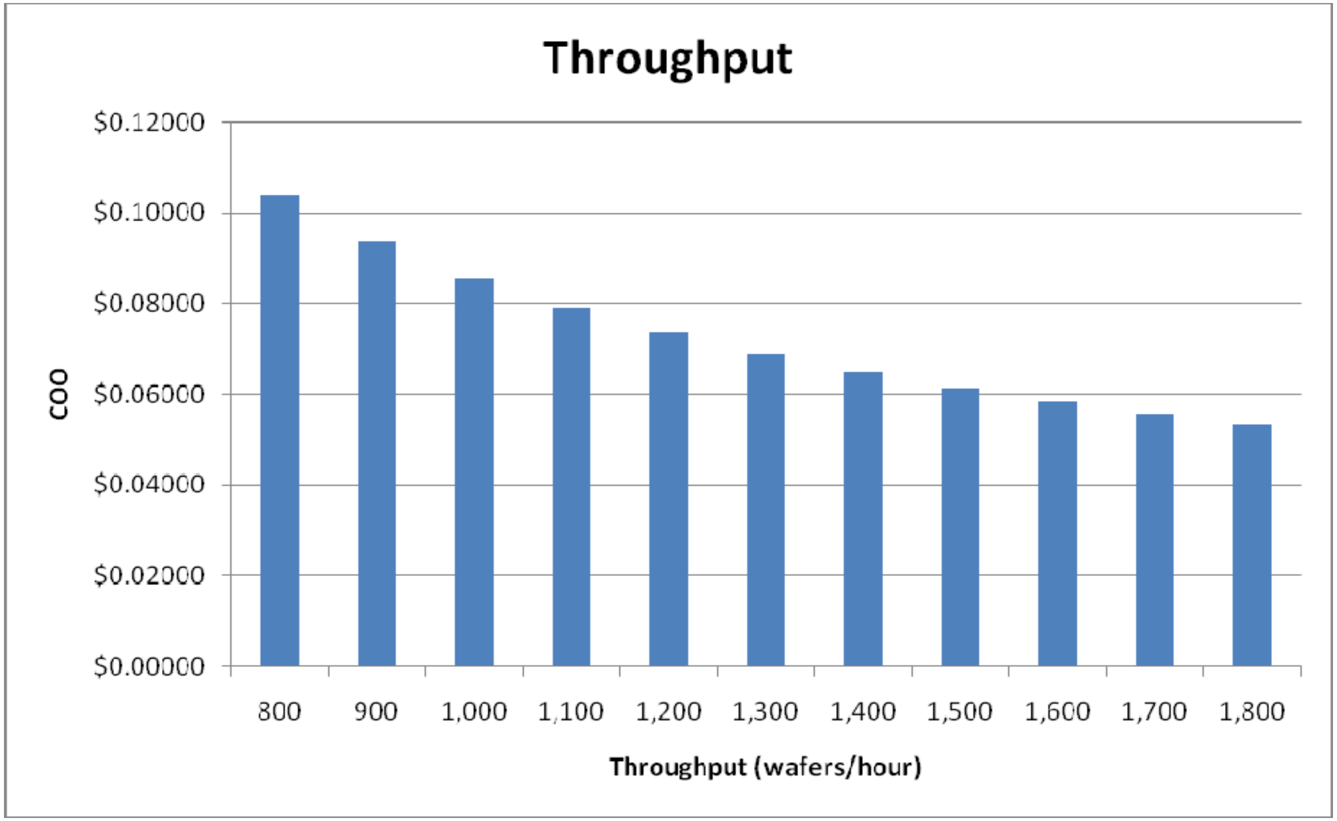
- Two possible impacts on depreciation costs
    - Purchase price
    - Throughput

Purchase Price Sensitivity



The COO impact is approximately 6% per $300,000 (20%) change in purchase price

Throughput Sensitivity



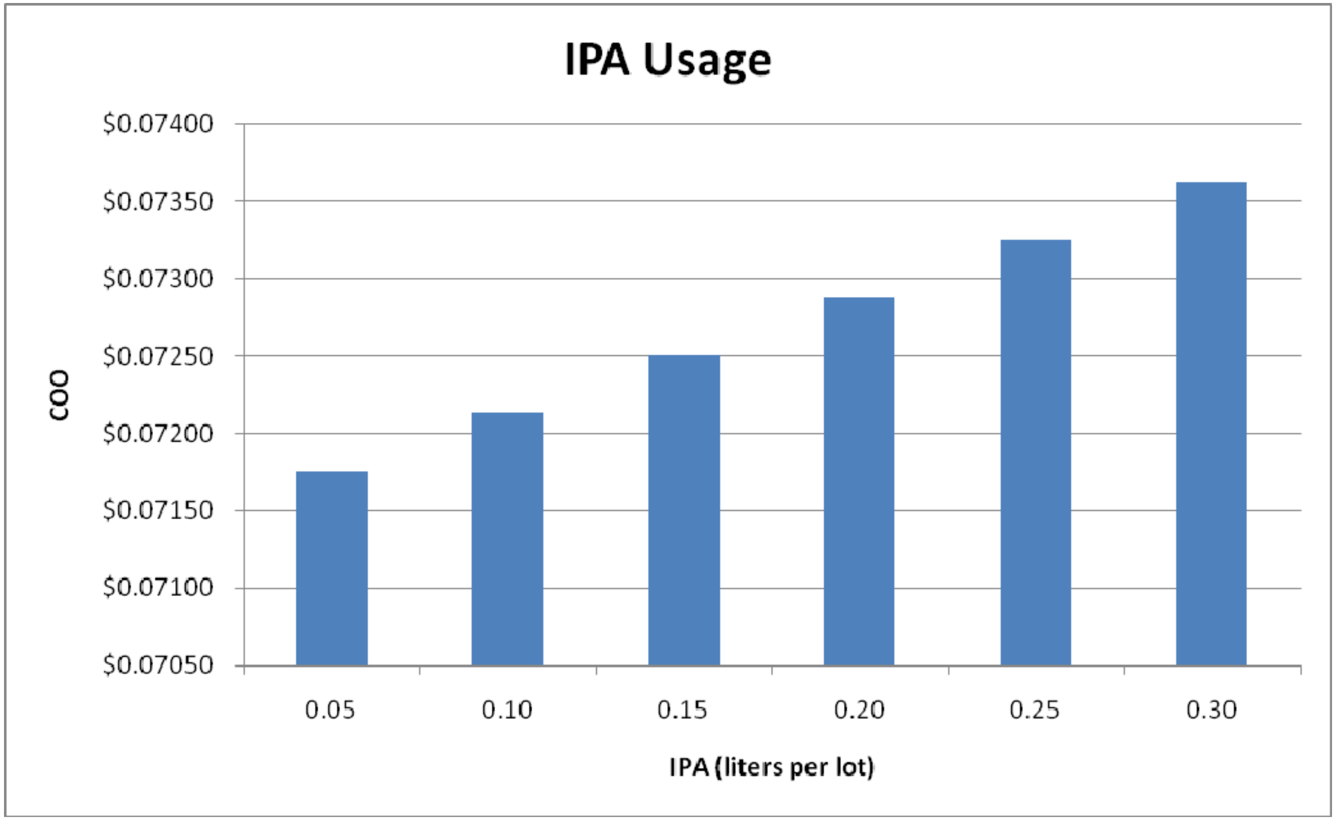
7% change in COO for a 100wph change around the nominal value
It is assumed that variable costs per cell do not increase with throughput

Supplies and Consumables

- One of the issues in defining a sensitivity analysis for any of the above items is their interrelationship with other factors
  - Increasing or decreasing KOH concentrations will have an impact not only on throughput, but also caustic drain costs
  - IPA is volatile at typical process temperatures (up to 90ºC) and that has a significant impact not only on IPA refresh but also exhaust volumes, which require oxidation
  - It is less likely that KOH concentrations can be significantly impacted due to the fact that it is the etchant, it is more likely that IPA can be impacted since it is acting as a wetting agent

Supply/Consumable	Annual Cost per System
DI Water	$ 16,046
HCl	$ 433
HF	$ 518
IPA	$ 20,131
KOH	$ 28,966
CDA	$ 234
H_2O_2	$ 1,638
Acid Drain	$ 7,127
Caustic Drain	$ 7,729
Exhaust	$ 20,741

IPA Usage Sensitivity



IPA, surprisingly, is not a major cost driver even as the industry moves to eliminate its usage

IPA Usage Sensitivity continued

- Reducing the volume of IPA or even eliminating it remains an industry concern
- Studies show that alternatives can be found although no solution has been endorsed by manufcaturing sites as of yet
- If we assume that an alternative surfactant can be used at:
    - 50% the cost of IPA
    - 10% the volume (with a corresponding 90% reduction in exhaust)
    - We calculate a COO of $0.07035 or a reduction of 4.5%
- Again, unless there are environmental or other strategic reasons, it appears replacement of a relatively inexpensive chemical like IPA is not a highly leveraged investment

Feed and Bleed COO

- Frequently, when using COO a proposed improvement results in an impact on multiple inputs
- For example, a feed and bleed approach to refreshing chemistry results in longer bath life and, hence, higher tool utilization
- The benefits of this approach can be quickly analyzed as follows:
    - A typical tool uses a bath for about 8-10 hours at the end of which the bath has to be changed
    - The time needed for the change out is approximately 1-2 hours, including the time needed to verify the right chemical concentration and the desired etch rate
    - A typical feed and bleed rate is to add additional chemicals of about 50% of the initial mix
    - This extends bath life and reduces chemical consumption
- COO calculations indicates that a feed and bleed system reduces the cost per wafer by nearly 16%

Conclusions

- Surface prep techniques will become more critical to obtain high efficiency solar cells and more robust processing
- Current POR and experience reasons may not be enough to understand effect of contamination. In-depth analysis to surface contamination and texturization patterns is indeed needed
- Industry continues to find ways to reduce cost of manufacturing e.g. IPA replacements, thinner wafers, automation, and higher throughput
- COO calculations indicates that a feed and bleed system significantly reduces the cost per wafer