Examining cost of ownership of crystalline-silicon solar-cell wet processing: texturization and cleaning

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ABSTRACT

This paper, the second in a series covering cost of ownership studies for photovoltaics [1], examines the need for saw damage removal and the follow-on processes of precleaning, texturization, and cleaning. The process considerations for wet and plasma approaches are further discussed before taking a detailed look at texturization using random pyramid formation. The paper will conclude with a view of current and future wet process techniques and a cost of ownership case study using Akrion Systems' GAMA-Solar as an example.

The need for saw damage removal, precleaning, texturization, and cleaning

In practice, there are four operations that are performed as part of the surface conditioning process in cell manufacturing. These are saw damage removal, precleaning, texturing, and cleaning. Saw damage results from the wire sawing process used to slice silicon ingots into wafers. As a result of this mechanical process, cracks of about 1-10μm deep are introduced into the surfaces of the wafer (see Fig. 1). Removing the saw damage from the wafer surface improves the mechanical strength of these thin wafers and increases the recombination at the surface region.

Precleaning removes surface contaminants on the wafer that can lead to differences in texturization feature sizes, which can have a direct effect on surface reflectance. Texturization is a light-trapping technique that increases light absorption, thus increasing energy production over a given surface area. Increases in light absorption can be accomplished through a variety of texturization techniques and/or through the application of antireflective coatings. Cleaning is the removal of metal, particulate, and organic contaminants that can negatively impact the performance of the solar cell in the short or long term. Ultraclean wafers are critical for obtaining high yields in the solar cell fabrication process.

Saw damage removal

Saw damage induced at the wafer-sawing level (Fig. 1) can be removed with either wet alkaline or acidic solutions that etch away at the top layer of silicon. Dry damage removal by plasma etching is also possible. Conveniently, the saw damage removal step can be combined in the same tool with the texturing step (Fig. 2).

Precleaning

Examinations of surface morphology indicate that reflectance variations are associated with the lack of homogeneity of texture features, as shown in the left-hand image in Fig. 3. Further analysis by scanning electron microscope (SEM) shows that this results from an abrupt change in pyramid sizes from one area to another, as shown in the right-hand image in Fig. 3. The area of low reflectance was found to correspond to the area of small pyramids, a texturing inconsistency that appears to have been caused by surface contamination on the wafers. Such contamination can be demonstrated by intentionally touching a precleaned wafer with a cleanroom glove and noting the dark patterns at the corresponding areas after texturization.

Texturization

Light management in the solar cell is critical. Silicon, a material with an indirect band gap, has a relatively low absorption coefficient. Efficient surface texturization, coupled with an antireflectance coating (ARC) (see Fig. 4), can reduce reflectance losses from 35% to below 10% [2,3].

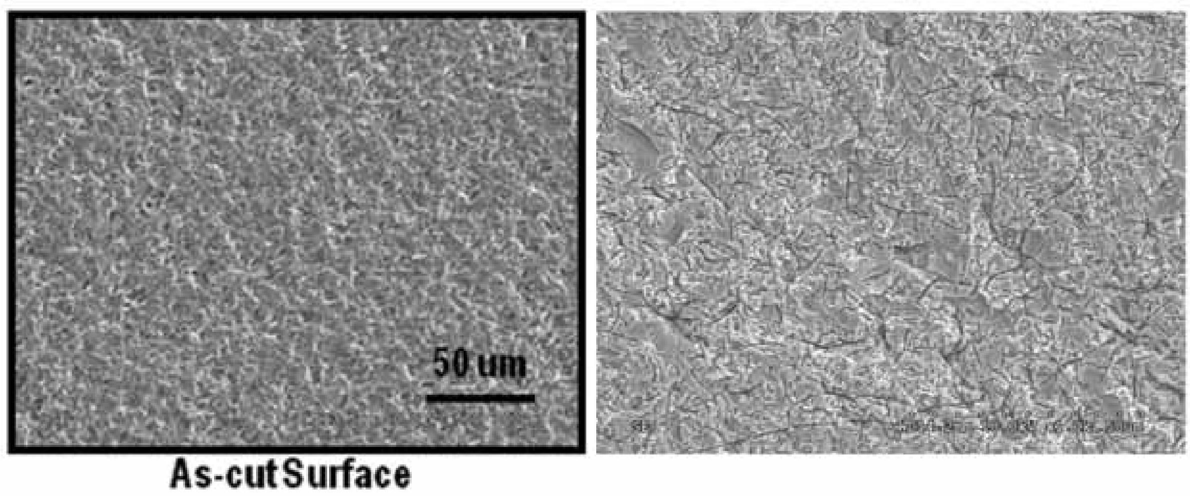

Figure 1. Wafer surface after ingot sawing.

Figure 2. Integrated saw damage removal, precleaning, texturization, and cleaning equipment.

As shown, a well-texturized surface reflects only 9.5% at 950nm compared to greater than 20% reflectance for an as-cut (untreated) surface.

The bonding energy of silicon atoms is different for each crystal plane – a characteristic that turns out to be very useful. Alkaline etching is not diffusion limited, instead it is driven by the differences in etch rate for the crystal planes. The result is that silicon etching is highly anisotropic and well understood in the industry. The <111> plane is more densely packed than the <100> plane and, thus, the etch rate of the <111> orientated surfaces are much less than those in the <100> orientation. An alkaline etchant exhibits an etch rate approximately 100 times faster along <100> than along <111> and, hence, the <111> facets are developed and form at 54.7 degrees to the horizontal plane. This result is the formation of small pyramids with a square base, randomly distributed over the wafer surface (see Fig. 5).

The degree of anisotropy (etch rate selectivity between different crystal planes), the etch rate, and homogeneity depend on the etching temperature, chemical concentration, and bath impurities. An additional factor to consider is that the typical etch bath creates residual etch byproducts. These silicates act as seeds (or nuclei) that initiate the pyramid formation and also act as an etch mask (or micro-mask) at that location. However, once these silica seeds exceed a critical concentration, they act as a contaminant, suppressing the etch rate sufficiently that the bath will no longer be effective in creating the random pyramid structures.

Cleaning

After texturing, the wafers are rinsed with deionized water, cleaned in HF and/or HCl to remove metal impurities on the wafer surface, and then dried in hot air (heated clean dry air or nitrogen). HCl removes surface impurities while HF removes the native oxide and any embedded impurities in the oxide, leaving the wafer surface free of trace metals and increasing the minority carrier lifetime. A metal signature of <5×10^{10} atoms/cm^2 could be obtained for Al, Cu, Fe, Mg, Mn, and Zn with this clean [4], increasing the minority carrier life time and improving the sheet resistance. This HF-last process renders the surface H-terminated and is highly desirable prior to high temperature phosphorous diffusion.

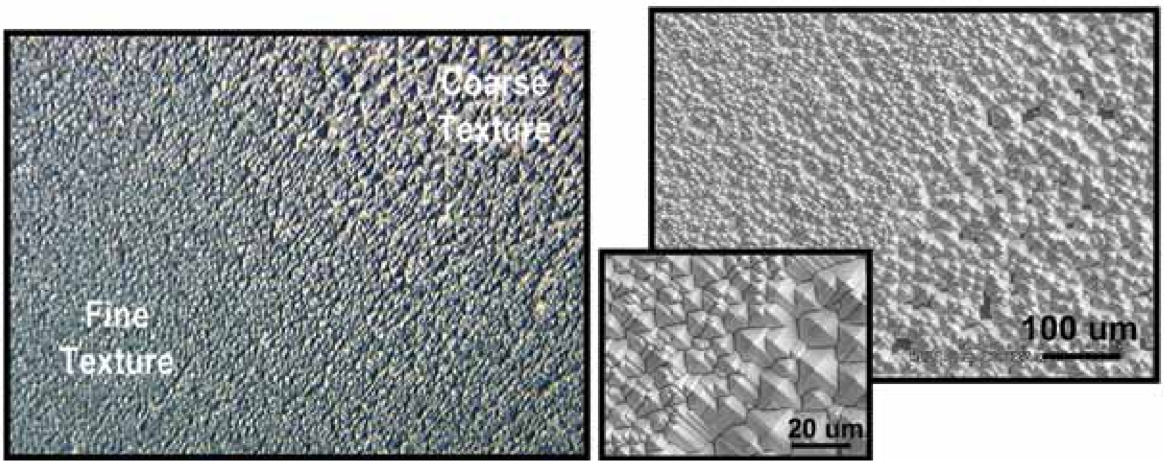

Figure 3. Surface morphology of an inconsistently textured area showing (left) optical microscopy image and (right) SEM image.


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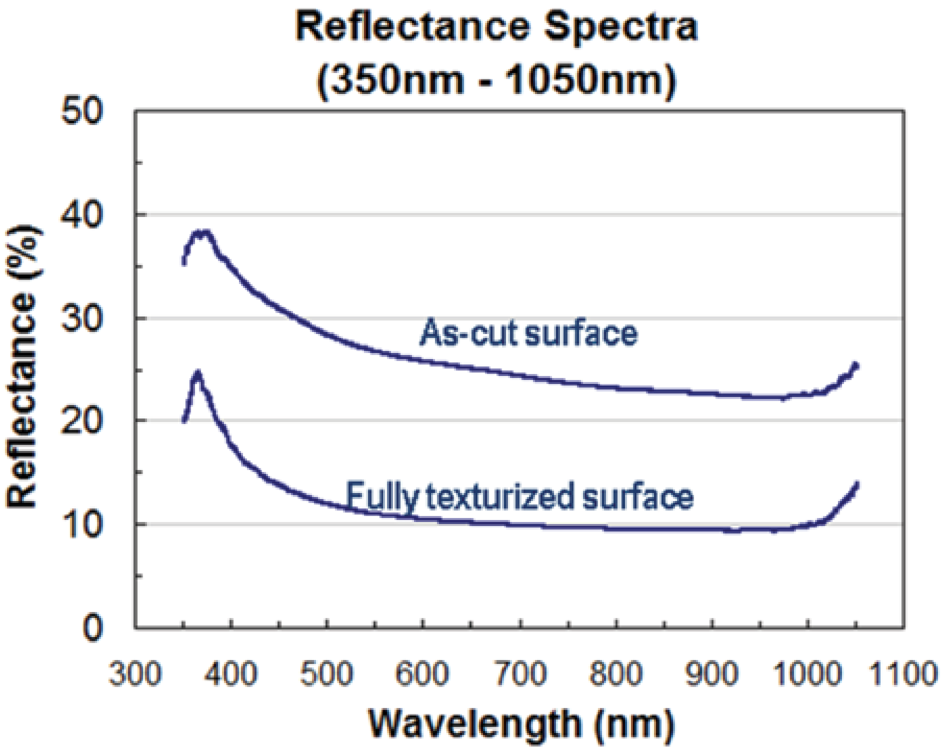

Figure 4. Reflectance with and without texturization.

Process choices: wet vs. plasma

Commonly used chemicals for this texturization are mixtures of KOH/IPA or NaOH/IPA. The IPA is a wetting agent for improving the lateral uniformity and anisotropy of the etching process. Alkaline concentration can vary from 2-5% to 10-20% by weight, while process temperatures can vary from 70-90°C. Depending on the desired results, process time can vary from a few minutes to an hour.

With increasing price pressure and COO concerns, tools can be specified to produce in excess of 3000 wafers/hour (wph). Tools are typically configured with multiple baths for the same chemistry and batch sizes of 200 wafers, which are held in cassettes and moved automatically from bath to bath. Wafers are typically exposed to this harsh chemistry for 30 minutes to produce these random pyramids. Inline processing has met with limited interest due to the length of the equipment needed to support such long process times.

It is worth noting that wet processes dominate the manufacturing base. Extensive learning that has been applied to wet processing has paved the way for high-quality, reliable, and productive tools. The materials themselves are readily available at high purity levels. While some might suggest this is a 'mature' process and thus has limited remaining upside, nothing could be further from the truth. In practice, it is this depth of understanding that allows for improvements to be made on a rapid basis, resulting in immersion batch tools like GAMA-Solar that incorporate the following features:

- Advanced process control (APC) using concentration sensors, ensuring repeatability, robustness and tool uptime needed for volume manufacturing.
- Low defects using advanced drying techniques leaving no streaks on the wafers. Ultrasonic/megasonics are often employed to further reduce defects in process and rinse tanks.

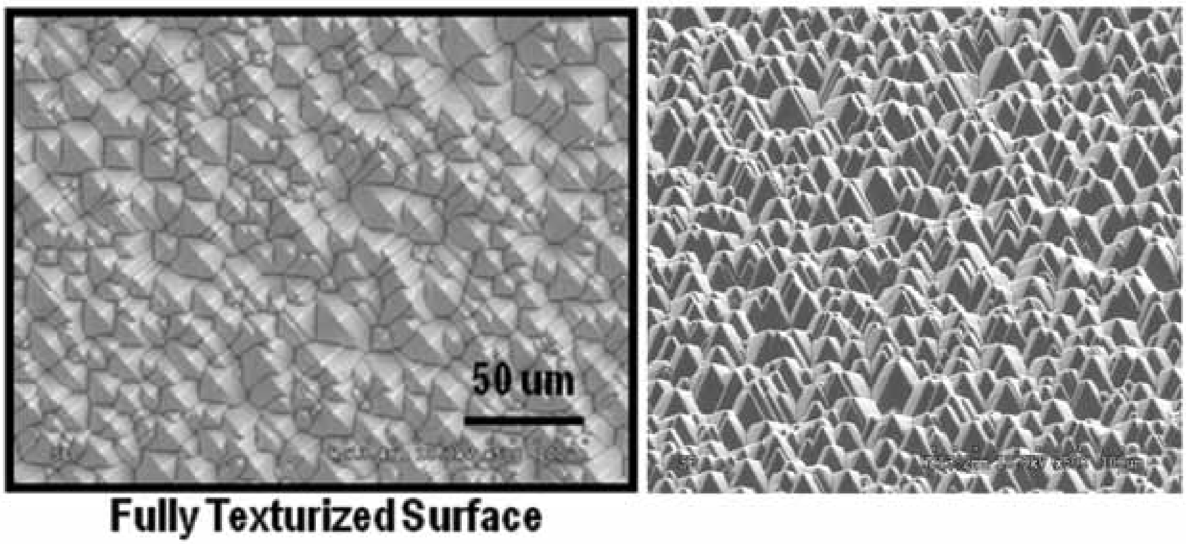

Figure 5. Random pyramid structures.

- Etch and texturization uniformity across the wafer, within wafers, and lot-to-lot by optimizing tank design for more uniform fluid flow.
- Tool reliability and flexibility by using modular designs that offer better control on water and chemical usage, exhaust volumes, and future upgradeability.
- Smaller footprint.
- All of the above having a positive impact on COO.

Plasma processes are relatively recent entrants into texturing. These processes have certain advantageous attributes when compared to wet processing, including reduced handling, reduced waste disposal, and reduced consumption of wet chemicals, such as DI water. In addition, as plasma etching is single-sided, it creates new possibilities for treating the backside of the wafer. These possibilities include the use of multicrystalline materials without saw damage, such as edge-defined, film-fed growth (EFG), which cannot be processed using common chemical bath texture methods.

A distinction has to be made between reactive ion etching (RIE) and other types of plasma texturing. RIE relies on the ion bombardment texturing, which results in a formation of so-called 'black silicon' and creates surface and subsurface damage that has to be removed for further cell processing (dopant diffusion).

RIE process chemistry is based on SF_6/O_2 or Cl_2. This technique has been proven to yield low reflectance with good uniformity, resulting in superior response in the long wavelength region. However, the defects induced by the ion bombardment can severely degrade the internal quantum efficiency (IQE). A possible solution is to use a damage removal etch (DRE), a wet chemical processing comprised of alkaline and acidic etch followed by modified acid-peroxide cleaning and final HF dip. DRE can partially diminish the results of texturing in terms of reflectivity; however, this is a necessary trade-off in solar cell processing to keep a low surface recombination velocity.

A second dry texturing alternative is a process based on microwave-powered antennas. These antennas are positioned above the substrates, providing sufficient radical density to cause chemical etching on the surface. Ions do not play a role in this process unless a radio frequency bias is applied. The process, which uses gases such as SF_6, N_2O and Cl_2, is self-masking in that the residues of the etching process are temporarily deposited on the surface, leading to a local etch block and the formation of a texture.

A third dry texturing process for silicon wafers was developed using a remote plasma source chemical downstream etcher, where the plasma is ignited by a microwave source situated above the reaction chamber that allows the ions to be trapped before reaching the wafer. In contrast to RIE, there is no acceleration of ions by a bias voltage as reactions on the silicon surface are carried out by radicals. Gases used are SF_6 and O_2; no ensuing wet chemical processing is required.

When plasma texturing is applied as a replacement for wet texturing in standard, thick (200μm) screen-printed solar cells, it yields similar or only slightly higher conversion efficiencies. In practice, the significant benefits of plasma texturing are most likely to be realized with advanced structures, with very thin wafers, and with specialized substrates such as silicon ribbons and epitaxial layers on low-cost silicon substrates. For these specialized substrates, plasma texturing is an enabling technology, as there is no straightforward wet chemical texturing process.

One important issue associated with plasma texturing is gas abatement. While replacing wet texturing by plasma texturing would reduce the amount of wastewater, the release of greenhouse gases could offset the environmental advantage associated with solar panels. SF_6, for instance, has a huge global warming potential (GWP) of 24,000. Just a small percentage of the SF_6 flow getting past the abatement system leads to a poor environmental balance, which is unacceptable for a PV product. This problem is common to several processes in microelectronics and increasingly to thin-film PV (reactor etching). Producers of gas and abatement systems have responded to the challenge and are developing solutions that can lead to zero release of GWP gas, either by effective recycling of the fluorinated species, or by offering alternative gas systems with low GWP [5].

In discussing the various trade-offs associated with texturing, it is apparent that there are numerous considerations. Nevertheless, the ultimate requirement is not a technical requirement, but a business necessity. It is critical to consider the trade-offs in processing not simply as a series of technical trade-offs, but as a series of business trade-offs. COO is a tool that can be applied to this analysis, resulting in a disciplined, objective analysis of the technical trade-offs.

Given the number of processes for saw damage removal, texturization and cleaning, a complete COO analysis of each technology along with each configuration is well beyond the scope of this paper. Instead, a configuration for a wet processing sequence will be evaluated, which the authors perceive as being commonly used in production today. The remainder of the paper will discuss this process and the associated cost of ownership.

Current state of wet processing

In considering a 30MW solar-cell production line, an analysis was performed to determine the required capacity of the texturization process step. The results showed a need to process 1200 wph using the following tool configuration:

- **Preclean**: using an alkaline etch to remove saw damage and preclean wafers prior to the texturization step.
- **Texturization**: using KOH/IPA tanks, with multiple tanks needed to support the throughput requirements.
- **Postclean using HF/HCl**: removing chemical residues and rendering the wafer surface metal-free.

Typical conditions

A 25-minute process time is achieved with 80°C in each KOH/IPA tank. Bath life is estimated to last for 24 hours with a feed-and-bleed mechanism, which permits the addition of small volumes of fresh chemicals and bleed of similar volumes of used chemicals. This helps keep the etch byproducts below the maximum threshold. Accumulation of etch byproducts will eventually work as an etch mask and heavily contaminate the wafer surface with silicates. Post clean typically comprises a 1:1:200 HF/HCl/Water at ambient temperature for five minutes, which achieves a bath life of five days.

Future process changes

The PV industry has enjoyed rapid and profitable growth. With increased competition and cost pressures, solar cell manufacturers are competing to produce high-efficiency solar cells at the lowest possible cost. Areas of opportunity in the wet processing arena include:

- **Chemistry change**. Efforts have already been made to develop texturization chemistries to replace IPA in the KOH/IPA mixtures [4,6]. Surfactants could replace IPA and provide equally texturized surfaces. In addition, plasma processes have shown promise to replace acidic texturing. However, the issue of gas abatement may offset the environmental advantages of less wastewater.
- **Automation**. Further automation can be employed to reduce wafer breakage and minimize/eliminate contamination.
- **Statistical process control (SPC)**. Recent trends show the need for process control. Tool manufacturers are offering sensors and technologies to monitor and control the concentration of chemicals over the bath life, which can lead to an accurate prediction of the chemical concentration required to produce the desired results. It also enables the extended use of chemicals and, hence, lowers COO and increases process robustness, and can contribute toward further reduction of the installation time as well as reducing rework and wafer misprocessing.
- **Tightened specifications**. This would require more sophisticated techniques for surface conditioning to eliminate foreign contaminations on the wafers. This may mandate that equipment makers build tools with stringent contamination (particles, metals) and etch uniformity specifications. It may also require including features like minienvironments for the tools, filtration of chemicals, and high-purity materials of construction, which would oblige solar cell manufacturers to adopt many of the same cleanroom protocols that are already in use in the IC industry.
- **Water consumption**. Just like the IC industry, wet cleans and etch processes use large volumes of water to remove chemicals from the wafer. Cost drivers and environmental pressures will force solar cell manufacturers to find ways to use less water by using dilute chemicals, for example, thereby needing less rinsewater.

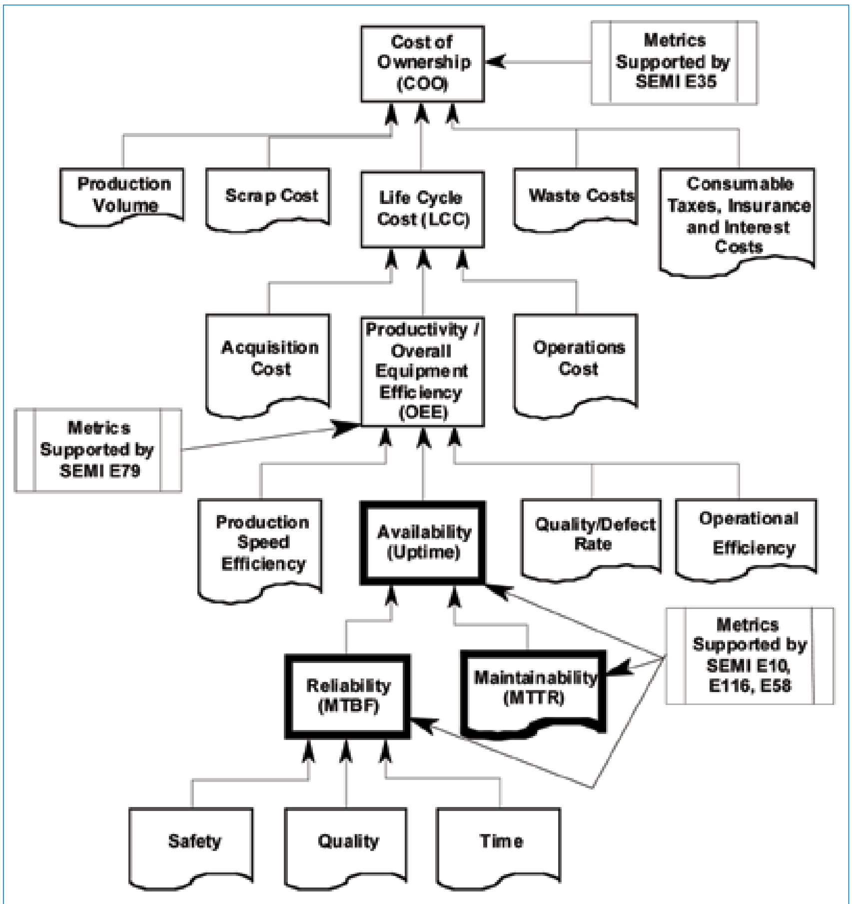

Figure 6. Hierarchy of equipment performance metrics [9].

Case study

As noted previously, a complete COO analysis of each technology along with each configuration, given the number of processes for saw damage removal, texturization, and cleaning, is well beyond the scope of this paper. Instead, a configuration for a wet processing sequence will be evaluated, one which the authors believe is commonly used in production.

Basic COO review

A more detailed discussion of COO can be found in the first paper in this series [1]. To review, the basic COO algorithm is described by [7]:

$$C_U = \frac{C_F + C_V + C_Y}{L \times TPT \times Y_C \times U}$$

Where:

C_U = Cost per good unit (wafer, cell, module, etc.)

C_F = Fixed cost
C_V = Variable cost
C_Y = Cost due to yield loss
L = Process life
TPT = Throughput
Y_C = Composite yield
U = Utilization

Overall equipment efficiency (OEE) review

One of the most popular productivity metrics is OEE [8], based on reliability (MTBF), maintainability (MTTR), throughput, utilization, and yield. All these factors are grouped into the following four submetrics of OEE.

- Availability (joint measure of reliability and maintainability)
- Operational efficiency
- Throughput rate efficiency
- Yield/quality rate.

Calculating OEE requires many parameters. If the accuracy requirement is not a critical factor, the following formula can be used to calculate an approximate OEE value:

OEE = Number of good units output in a specified period of time/(theoretical throughput rate × time period).

There are many equipment performance metrics at different levels. Fig. 6 depicts the hierarchy tree of the equipment performance metrics.

Parameter	GAMA-Solar
Throughput	1,200 wafers/hour
Wafer size	156mm
Wafer cost	$3
Mean time between failure (MTBF)	1,500 hours
Mean time to repair (MTTR)	4 hours
Equipment cost	$1,500,000
Equipment yield	99.96%
Utilities	$30,700/year/system
Consumables	$103,563/year/system
Maintenance	Owner provided

Table 1. Major COO inputs.

Wet processing for texturization and cleaning

As stated previously, an obvious requirement for high efficiency in photovoltaic modules is low reflectance. Single-crystal silicon solar cells achieve very low reflectance through use of textured surfaces and/or antireflection coatings [2-4,6,10]. These principles have been understood and employed for more than a decade. The rest of this paper will examine the current cost structure and potential for cost reductions in a state-of-the-art, production-proven wet processing tool from Akrion Systems: the GAMA-Solar.

COO inputs

The following are the results of the COO analysis run on the GAMA-Solar wet processing station, based on the major input parameters shown in Table 1.

In addition to the parameters depicted in Table 1, where required, example values from SEMI E35 for administrative rates and overhead were used. These values were provided by SEMI North American members and may not be applicable to other geographic regions. However, it is the author's experience that these example values do not impact the COO results on a relative basis.

Cost drivers

Examination of the detailed TWO COOL cost-of-ownership model in Table 2 highlights the main cost and productivity factors (TWO COOL is a commercial software package from Wright Williams & Kelly). Recurring costs are approximately 1.5× initial capital costs over the life of the process.

Table 3 takes a closer look at the cost breakdown according to the 13 categories specified in SEMI E35. The top pareto costs are labour; depreciation, which is impacted by equipment costs, throughput rate, and utilization; materials/consumables, which includes utilities, supplies, consumables, and waste disposal; maintenance, including repair parts and technician labour; and floor space.

The top three cost drivers account for almost 90% of the total cost of ownership. For this reason, attention will be focused on those areas as cost sensitivities to input parameters are examined that drive labour, depreciation, and material/consumables costs.

Cost driver sensitivities

The first factor to be examined is labour content, which represents 40% of the total cost of these integrated process steps. Labour is defined as direct operator labour and the model is based on one operator overseeing one machine. Since these are highly automated machines with sufficient throughput to support a 30MW line, it is not likely that the factory would be significantly larger in order to allow for further amortization of labour content. However, Fig. 7 does examine COO sensitivity to labour content, should such opportunities present themselves.

If the factory can scale to accommodate two machines (or an equivalently larger single machine), increasing the labour efficiency from one to two machines would improve COO by 20%. Given such a significant sensitivity, looking at scaling and automation issues would be a major opportunity for cost reductions.

Next, the factors impacting depreciation, purchase price and throughput are examined (see Figs. 8 and 9). Purchase price has a modest impact on COO in high throughput tools, especially those with higher variable costs. The cost impact in this case is approximately \$0.004 (6%) per \$300,000 (20%) change in purchase price. However, as can be seen in Fig. 9, improvements in throughput can have a significant impact

Cost per system	\$1,500,000
Number of systems required	1
Total depreciable costs	\$1,532,500
Equipment utilization capability	96.72%
Production utilization capability	96.72%
Composite yield	99.96%
Good wafer equivalents out per week	194,908.54
Good wafer equivalent cost	
With scrap	\$0.07362
Without scrap	\$0.07242
Average monthly cost	
With scrap	\$62,353
Without scrap	\$61,336
Process scrap allocation	
Equipment yield	100%
Defect limited yield	0.00%
Parametric limited yield	0.00%
Equipment costs (over life of equipment)	\$1,664,627
Per good wafer equivalent	\$0.02340
Per good cm^2 out	\$0.0001
Recurring costs (over life of equipment)	\$3,573,012
Per good wafer equivalent	\$0.05022
Per good cm^2 out	\$0.0003
Total costs (over life of equipment)	\$5,237,639
Per good wafer equivalent (cost of ownership)	\$0.07362
Per good wafer equivalent supported	\$0.07362
Per good cm^2 out	\$0.0004
Per productive minute	\$1.47

Table 2. COO results.

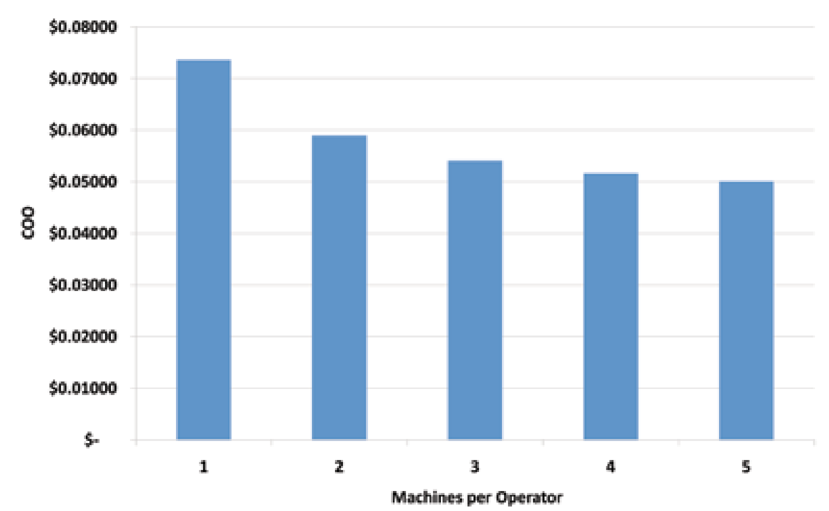

Figure 7. Sensitivity analysis of labour vs. COO.

Cost drivers per good wafer equivalent	
Labour	\$0.02940
Depreciation	\$0.02154
Material/consumables	\$0.01491
Maintenance	\$0.00338
Floor space costs	\$0.00167
Support personnel	\$0.00134
Scrap	\$0.00120
Training	\$0.00010
System qualification costs	\$0.00009
ESH preparation and permits	\$0.00000
Moves and rearrangements	\$0.00000
Other materials	\$0.00000
Other support services	\$0.00000

Table 3. Pareto of cost drivers.

on COO, with a $0.006 (7%) change for a 100wph change (8%) around the nominal value.

Assumed in this sensitivity analysis is that the amount of chemistry consumption per wafer remains the same across all throughputs. If higher per-wafer chemistry consumptions are needed to achieve the increased throughput (increased consumption of acids, bases, and IPA), then this becomes a multivariable analysis and beyond the scope of this paper.

The last area of examination for cost sensitivities is supplies and consumables. Table 4 shows the annual costs per system by supply item. One of the issues in defining a sensitivity analysis for any of the listed items is their interrelationship with other factors. Increasing or decreasing KOH concentrations, for example, will have an impact not only on throughput, but also caustic drain costs. Likewise, IPA is volatile at typical process temperatures (up to 90°C) 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.

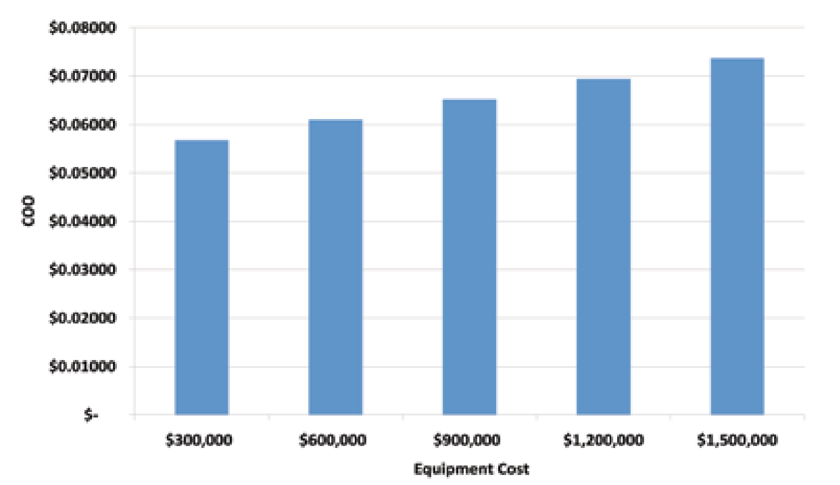

Figure 8. Sensitivity analysis of purchase price vs. COO.

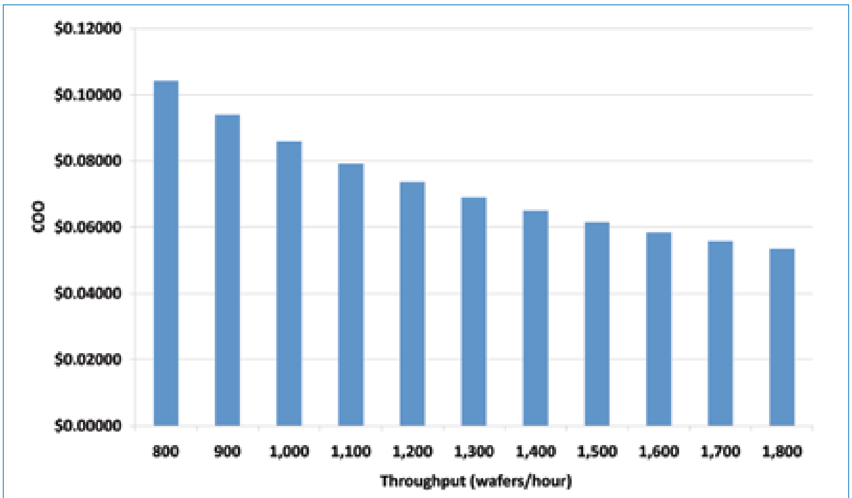

Figure 9. Sensitivity analysis of throughput vs. COO.

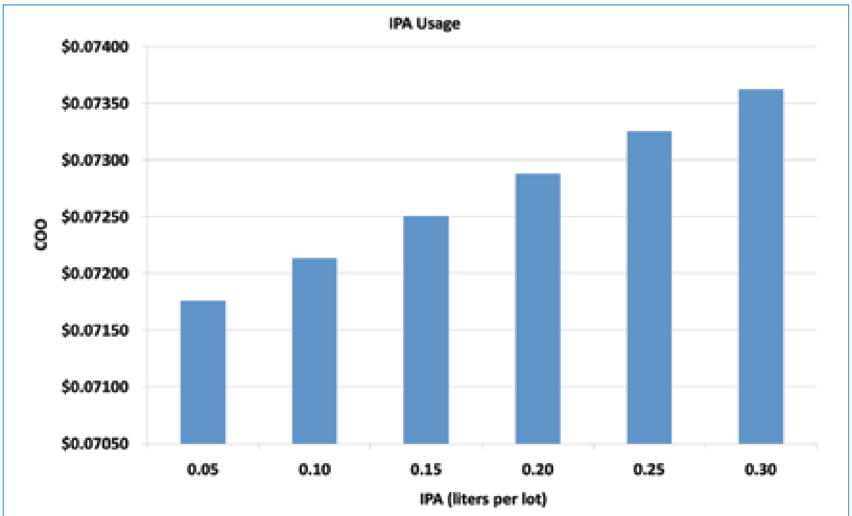

Figure 10. Sensitivity analysis of IPA usage per lot vs. COO.

Fig. 10 looks at the COO impact of reducing IPA consumption. In preparing for this paper, the survey of end-users indicated that their perception was that IPA was a major cost driver due to its volatility at operating temperatures. As a result, Fig. 10 was a surprise based on these initial comments and shows that efforts solely focused on IPA usage reduction will not drive a major cost reduction.

However, reducing the volumes of IPA or even eliminating it remains an industry concern. Studies show that alternatives can be found although no solution has been endorsed yet by manufacturing sites. If the assumption is that an alternative surfactant can be used at 50% the cost of IPA and at 10% the volume (with a corresponding 90% reduction in exhaust), a COO of $0.07035 is calculate, 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.

When using COO, a proposed improvement can often result 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, extending bath life and reducing chemical consumption. COO calculations indicate that a feed-and-bleed system reduces the cost per wafer by nearly 16%.

Overall equipment efficiency

Table 5 shows the OEE of the GAMA-Solar; the OEE is in excess of 95% which leaves little room for improvement, with only five hours per week dedicated to preventive maintenance.

Conclusion

This paper has examined the need for saw damage removal and follow-on

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

Table 4. Annual supply/consumable costs.

Overall equipment efficiency	96.68%
Availability efficiency	96.72%
Engineering usage	0.00 hr/week
Standby	0.00 hr/week
Hours available/system (productive time)	162.49 hr/week
Downtime	5.51 hr/week
Scheduled maintenance	5.04 hr/week
Unscheduled maintenance	0.47 hr/week
Test	0.00 hr/week
Assist	0.00 hr/week
Non-scheduled time	0.00 hr/week
Equipment uptime	162.49 hr/week
Total time	168 hr/week
Performance efficiency	100%
Throughput at capacity/system	1200 layers/hr
Theoretical throughput	[1200 layers/hr]
Operational efficiency	100%
Rate efficiency	100%
Quality efficiency	99.96%
Equipment yield	99.96%
Defect limited yield	100%
Parametric limited yield	100%
Alpha error factor	100%
Beta error factor	100%
Redo rate	0.00%

Table 5. OEE results.

processes including texturization in both wet and plasma-based systems. While the technical approach to reducing reflectance at the wafer's surface is well understood, the results show that initial industry concerns over the cost of IPA may have been misplaced. Through the use of COO, the photovoltaics industry has at its disposal a quantitative methodology which can help it make the best choices as it continues down its rapid cost decline curve.

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