Steamer vs. torch in PV manufacturing—a cost of ownership comparison

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This article looks at the cost advantages of using purified steam instead of torches in photovoltaic manufacturing processes.

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Introduction

Improvements to first generation solar cells will require the use of lower cost multicrystalline (mc)-silicon, thinner wafers and additional oxide layers to improve cell efficiency. Higher efficiency can be achieved through the addition of front and rear oxide passivation layers. Dry oxidation is too slow at low temperatures and at high temperatures prevents the use of lower cost multicrystalline silicon wafers. This is driving the industry to add a wet oxidation step to grow the passivation layers.

In wet thermal oxidation, steam or water vapor is added to accelerate the oxidation growth rate. Oxide is the critical material in wet thermal oxidation, so the method of generation determines the yield and throughput, and the ultimate success of the device in the marketplace. Any improvements in the steam generation process go straight to the bottom line. This article looks at the cost advantages of using purified steam instead of torches in photovoltaic manufacturing processes.

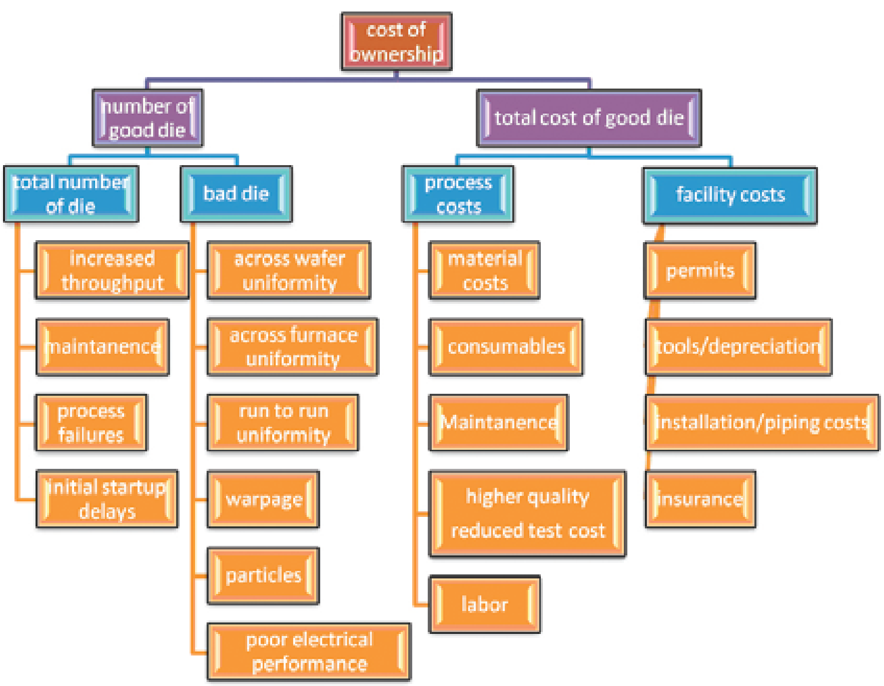

Chart 1. Key oxidation factors affecting profit.

Key oxidation factors affecting profit

Many factors are involved in calculating the total cost of ownership. These can be grouped into two categories: factors related to yield (number of good die) and factors related to cost (total cost of all die)—see *Chart 1*.

Yield

Yield is defined as the number of die that pass final test. The total number of die per unit time is a function of throughput, which is controlled by the process recipe (growth rate), plus maintenance time and unscheduled work stoppages. The throughput calculation should also include start up delays with equipment, installation and permits because these affect the market window and cannot be recovered.
Total bad die (yield loss) is subtracted from the total die and is related to problems with across-wafer uniformity, wafer-to-wafer uniformity, and run-to-run uniformity, warpage, particles and overall film quality or electrical performance.

Cost

Process cost is the sum of materials consumed during oxidation, consumables used to process the wafers, maintenance parts, labor to process and maintain the tools, and testing associated with the quality level attained by process control.

Facilities cost include the cost to prepare the facility to grow oxide, tool cost and depreciation, installation and piping, permits, inspections, and insurance that takes into account safety.

Steam generation options

The steam generation method affects all oxidation factors that affect cost of ownership. The two primary options are:

- **Pyrolytic Torch**. High purity hydrogen and oxygen gas combine to form steam that then diffuses oxygen into the silicon wafer, forming the TOx layer.
- **RASIRC Steamer**. De-ionized water is vaporized then passed through a non-porous hydrophilic membrane, creating ultrapure steam at a controlled positive pressure that then flows to the furnace.

Maximizing good die

To provide a better understanding of how the choice of steam generation affects yield, each technique is discussed in terms of throughput and film quality.

Throughput and growth rate

Oxide growth rate can be increased by increasing the partial pressure of water vapor[4]. While this may seem obvious, technical difficulties interfere with increasing the actual quantity of delivered water vapor.

According to the model of Deal and Grove[4], the growth rate of the oxide layer is directly related to the effective diffusion of the water molecules into the oxide layer and the equilibrium concentration in the immediate area. When a carrier gas is used to deliver water vapor, the carrier gas molecules generate a partial pressure. This partial pressure lowers the partial pressure of water vapor and slows the diffusion of water into the oxide film. The result is lower driving force and slower growth rate. For a given temperature and process pressure, oxide growth rates are fixed if the gas ratio is also constant. However, for a given operating temperature, this growth rate is not maximized until the water vapor pressure is equal to 100% of the operating pressure.

- **Pyrolytic Torches**. Torches cannot provide 100% water vapor due to accuracy limits of mass flow controllers (MFCs). The reaction rate (growth rate) will vary over time because the MFCs will drift, again affecting repeatability and throughput. In addition, for safety reasons there must always be excess oxygen to ensure against combustion. As a result, it is not uncommon to have 10% oxygen and 90% steam. This increase in oxygen flow reduces the partial pressure of steam, thereby reducing the growth rate.
- **Steamer**. Using a proprietary membrane developed by RASIRC, the Steamer admits 100% saturated purified steam into the process tube. The flow rate of the steam is measured and controlled. Delivery of 100% saturated steam ensures the highest oxidation rate (shortest time). The positive pressure eliminates the need for a carrier gas and minimizes back streaming into the furnace. The Steamer compares favorably to the torch, as illustrated in *Figure 1*.

Throughput, process interruptions and maintenance

The number of good die is not only dependent on device yield, but also on tool uptime. Planned and unplanned downtime directly reduces the amount of wafers that can be oxidized. Each steam delivery method has inherent reliability levels.

- **Pyrolytic Torch**. Pyrolytic torches burn hydrogen at 2000°C. This high temperature generated by the combustion of the hydrogen creates several key reliability challenges. The torch must be cooled either by water or compressed air. Even with this cooling feature the heat causes torch components to break down and require maintenance every six to 18 months. The safety system also needs to be verified at this time. This usually requires at least two days of down time per shutdown. In addition, the use of hydrogen delays the startup of a new furnace system because permits are required and a safety check needs to be completed. The safety interlock system typically fails every 18 months. This can lead to the loss of a complete load of wafers. Thick oxide conditions, which require long run times, are especially difficult on torch components due to prolonged thermal abuse. It is not unusual to lose four days per tube per year for planned and unplanned service.
- **Steamer**. The Steamer does not require hydrogen or oxygen to generate water vapor. The non-porous membrane provides both control of the steam flow rate and a barrier between liquid water and the furnace tube. The redundant thermal control system and the minimal amount of moving parts provide a reliable steam delivery system, especially when running long multiday to multi week processes. Extensive field testing has shown minimal maintenance and high reliability under demanding process conditions.

Uniformity

For wet thermal oxidation, the partial pressure at the wafer surface determines the local growth rate. Any air or oxygen will

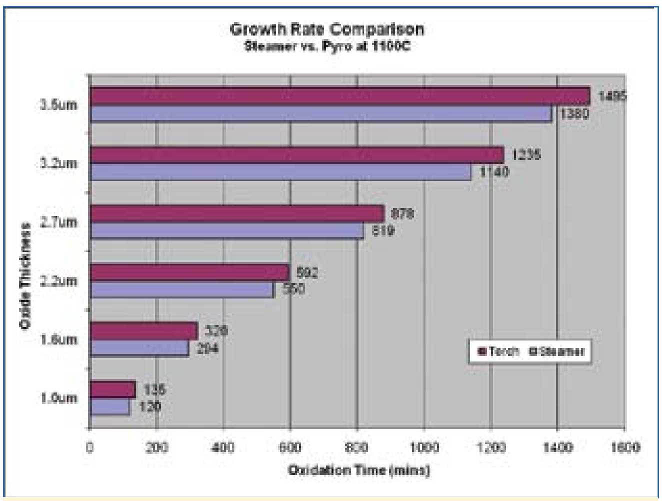

Figure 1. 7% improvement in growth rate of a Steamer over a pyrolytic torch.

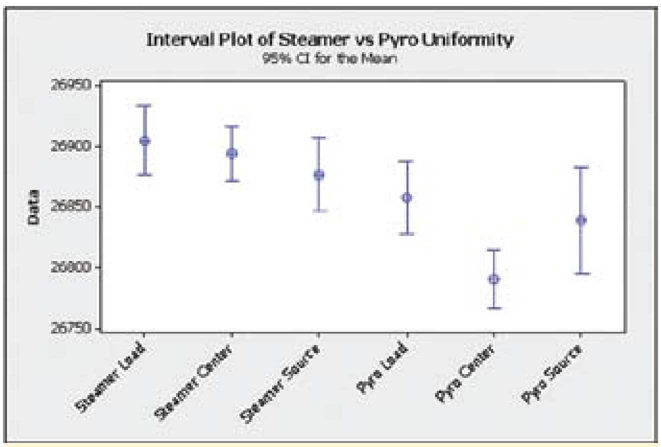

Figure 2. Steamer shows improved within-wafer and cross-load uniformity over Torch source and is well within specification limits. Illustration is across 125 wafer loading (175 wafer total).

reduce this growth rate. Because furnaces are not gas tight, some ambient air typically back streams around the load door into the furnace. The higher the flow rate of steam, the less likely air will be able to affect the wafer load. In addition, the water vapor must be completely vaporized to generate the same water vapor conditions throughout the furnace.

- **Pyrolytic Torches**. Both the cost of burning oxygen and hydrogen and the high temperature lead to process decisions that ultimately adversely affect uniformity. High steam volumes lead to high cost. High heat load leads to front-to-back problems. To minimize these issues, the process engineer will run the minimum steam needed. The resulting low steam flow rate leads to uniformity problems at the load door, and these problems are accentuated as the tools wear out.
- **Steamer**. The Steamer uses a membrane to deliver 100% saturated purified steam into the process tube. The flow rate of the steam is measured and controlled, enabling the Steamer to ensure the highest oxidation rate (shortest time) and the highest CpK (best uniformity). The water vapor ratio can be easily increased because the process of generating steam directly from water removes the limits typical with torches, bubblers, and DLI. This ability to substantially raise the flow rate can overcome process challenges such as leaky furnace load doors and loading concentricity issues. By maximizing flow rate with 100% steam the optimum growth zone within the furnace is increased, leading to more wafers per run that meet good die standards.

Contamination including warpage, particles, and electrical performance

Any process equipment used to generate an oxidizing ambient must first be capable of producing a contamination free environment. The devices being produced must not be exposed to metals, carbon, organic materials, and solids. Contaminants lead to damaged devices and loss of overall throughput. The creation of the steam must be 100% to prevent droplet formation that can carry ionic contamination as well as create localized cooling which will lead to warping.

- **Pyrolytic Torches**. As the torch burns, the injector itself is consumed at a rate determined by flow rate and accelerating with continuous operation. This silica makes its way into the furnace and onto the wafers. In addition, the water vapor generated is only as pure as the original gases. Any contaminant in the gases will transfer to the furnace and the wafers. The thermal profile created by the torch can lead to a large thermal shadow which affects wafer-to-wafer uniformity.
- **Steamer**. The Steamer uses a non-porous hydrophilic membrane that selectively allows water molecules to pass. The membrane is 1,000,000 times more selective for water molecules compared to nitrogen molecules. In the vapor phase, the membrane only allows water. All other molecules are greatly restricted, so contaminants in water such as dissolved gases, ions, TOCs, particles, viruses, bacteria, pyrons, and metals can be removed in the steam phase. All wetted components in the liquid path are quartz or Teflon®. The purified steam path components are quartz and Teflon® fittings and valves.

The Steamer maintains the water reservoir at a constant boil preventing the growth of bacteria. This system is also equipped with an automatic purge feature to flush the boiler at start up.

Process costs

There are a variety of gases and liquids used to generate steam for oxidation. The combination required determines the relative cost of the process.

- **Pyrolytic Torch**. Both hydrogen and oxygen are required to generate vapor using a torch. In addition the heat generated through combustion must then be removed with compressed air or cooling water, increasing power costs. This is independent of the labor load associated with the hydrogen and oxygen support required for the torches. Some facilities will not allow torches to run untended which requires personnel onsite throughout the run and limits third shift and weekend facility operation.
- **Steamer**. The Steamer requires DI water and CDA. The elimination of oxygen typically keeps material costs to less than $0.0025/hr. A key aspect to keep in mind is the cost savings generated by better uniformity. The elimination of rework and inspection time to sort through uniformity scatter can be eliminated through the Steamer's improved wafer-to-wafer uniformity. Also, some thick oxide customers would have to run wafers to grow additional oxide if the film was thin. This is difficult and labor intensive. As the uniformity can be improved from >5% to less than <1.2% rework can be eliminated, with a large reduction in associated labor.

Maintenance costs

- **Pyrolytic Torch**. Maintenance costs associated with pyrolytic torches are often unexpectedly high. This is due to several factors associated with their design. Because of the safety issues involved with the use of hydrogen many redundant interlocks are used on torches to ensure safe operation. Unfortunately, these components must operate near extremely high temperatures and as a result their failure rate is high. It is therefore typical to schedule maintenance at periodic intervals to prevent failure. During this scheduled maintenance various components (e.g., thermocouples, flame detectors, lamps, heaters, injectors) are replaced, the quartz components cleaned, and MFCs calibrated (H2). The frequency of this is typically two to three months and may take a day to complete. Injector's can cost between $200 and $2000. TCs cost $200 each and the associated costs related to lost productivity and labor can be over $100,000 per event.
- **Steamer**. Maintenance and labor associated with operating the Steamer is negligible. The membrane filter is a cross flow device that does not clog or lose efficiency under normal operating conditions. The primary maintenance task is to track heating element (lamp) hours for predicted replacement times. This is recommended to be every six months or longer and takes approximately 30 minutes.

Facilities costs

When looking at new installations, whether green field, facility expansion, or dry to wet oxidation conversion, it is important to review both material and infrastructure costs as well as permitting requirements.

- **Pyrolytic Torch**. Torches require either a bulk hydrogen and oxygen facility or point of use gas cabinets. Bulk facility installations of hydrogen and oxygen use large truck trailers or cryogenic tanks. The bulk gases are then filtered, purified and piped to each furnace. Many municipalities highly regulate these installations and generally prohibit permitting in areas where other businesses or residences might be affected by a leak or explosion. In addition to permitting issues, infrastructure investment is high for the tank farm installation as well as the piping of all welded high purity stainless steel lines. In some areas double containment may be required. Installation costs can run over $200 per foot and piping may extend hundreds or thousands of feet in larger installations.

Point of Use (POU) installation places a gas cabinet near the tool or in a chase area. For oxide thicker than 100 nm, hydrogen and oxygen usage can require frequent cylinder change out. The cost of the gases often is less than the labor required to change out and purge the lines. When dealing with pyrophoric gases, two operators may be needed to meet safety regulations. The same piping costs generally still apply as well as hydrogen safety interlocks to prevent excessive hydrogen from reaching the tool without the matching oxygen flows. Because cylinders must be changed out frequently, storage within the building may be limited, requiring additional space external to the building for flammable gas storage. Permitting can again become a problem and limit or slow the expansion of the facility to add wet thermal oxidation capacity.

- **Steamer**. The DI water plant infrastructure can be used without incurring significant additional costs. The DI water for each Steamer is less than 1.5 liters per hour which should not affect the DI water plant. Lines can be run ¼" or 6 mm PFA tubing. Installations can typically be done at minimal cost by in-house facility engineers or local mechanical contractors without extensive permits and safety issues.

Cost of safe operation

Safety is a big concern for manufacturers. Processes that involve volatile gases are inherently more dangerous than those that do not. The cost associated with safe operations is higher for processes that involve such gases.

- **Pyrolytic Torch**. This process is inherently dangerous because of the high temperature and volatile gases. Additional oxygen is required to ensure that the hydrogen is sufficiently saturated.
  - **Steamer**. Inherently safe

The torch has a higher cost of safe operations due to the use of oxygen to dampen the hydrogen. This excess oxygen serves no other purpose than to reduce the chance of explosion.

Cost Calculator

Many factors go into the cost of ownership calculation, making it difficult for the typical manufacturer to get a quick comparison of the options available. RASIRC has built a calculator that takes a dozen inputs and presents an immediate calculation of the ROI period, total annual savings, and throughput enhancement provided by the Steamer. This calculator can be found at *www.RASIRC.com\roi\torch.php*.

Inputs are grouped into:

- Wafer Processing: Process value/wafer, wafers/furnace run and hours to grow oxide
- Process Gas Volumes and Power Consumption: H2, O2, Power and CDA
- Costs: H2, O2, CDA, Electrical cost and spares

Behind the scenes, these inputs are calculated to estimate the incremental value of the Steamer over Torches. Based on the results, manufacturers can decide for themselves whether the potential reduction in cost of ownership is worth pursuing.

A simplified example is given in *Table 1* for a 2.7 micron thick oxide film run. The Steamer was set to 16 slm and the torch was set to a 15 slm hydrogen and 8.5 slm oxygen flow. The enhanced growth rate and reduced operated cost generated a $127,000 savings over the torch. This hydrogen cost is based on bulk rates. Gas cylinder rates would be five times higher.

Conclusion

The ability to turn water directly into steam and then purify the steam creates a new paradigm in the technique to create steam for wet oxidation. The benefits of eliminating hydrogen include safety, material cost reduction, and increased growth rate and uniformity. Steam generation using the Steamer creates both top and bottom line improvement through increased good die and reduced operating cost.

References

1. Spiegelman, Jeff. "Alternative Method and Device to Purify and Deliver Water Vapor".
2. Spiegelman, Jeff. "Urea and Ammonia Removal from De-Ionized Water via Steam Purification".
3. Spiegelman, Jeff. "Improved Oxide Growth Rate and Uniformity through New Steam Delivery Method".
4. Deal B. E. and Grove A. S. 1965 J. Appl. Phys. 36 3770
5. Geib, K.M., Choquette K.D., Hou H.Q., and Hammons, B.E. "Fabrication issues of oxide-confined VCSELS". Center for Compound Semiconductor Technologies. Sandia National Laboratories

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Wafer Processing	Steamer 101	Torch
Hours to grow oxide lasyer	12.00	12.84
Total process time, in hours (including ramp up/down)	15.00	15.84
Wafers/run	144.00	144.00
Wafers/hour	9.60	9.09
Wafers/week	1612.80	1527.27
Process value/wafer	25.00	25.00
Total wafer value processed/week	40,320.00	38,181.82
Total utilities cost, weekly	27.23	294.50
Total maintenance costs, annually	2900.00	13,100.00
Annual utilities + maintenance cost	4,315.79	28,413.93
Annual throughput	2,090,895.78	1,963,696.14
Annual throughput loss relative to steamer	0.00	127,199.64
Total annual cost difference	0.00	-127,199.64

Table 1. Cost comparison of torch vs. steamer.