Boosting performance and reducing the cost of thin-film photovoltaics with rotary magnetrons

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ABSTRACT

A variety of thin-film technologies are now entering a volume manufacturing phase. The benchmark has already been set by First Solar, Inc. in its conversion efficiencies, volume ramp and lowest cost-per-watt in the PV industry. Large-area thin-film deposition is a critical process step, dictating cell performance, reliability and manufacturing throughput. However, adoption of thin-film solar cells has been limited in the past by relatively complex and costly manufacturing processes.

The advent of rotating cylindrical magnetrons for sputtering is demonstrating the potential to significantly reduce thin-film manufacturing costs. In this paper we discuss the basics of the technology and the developments taking place with some of the leading suppliers of sputtering target technology for the PV industry.

Technical barriers to volume production of thin-film technologies and market acceptance are declining rapidly. Although the current economic environment has affected many thin-film start-ups, causing them to delay or reduce planned ramps, the majority of market researchers expect a rapid growth in thin-film production over the coming years.

The Prometheus Institute expects thin-film technologies to make up 35% of all module production by 2010, equating to just over 8GW. Figure 1 shows a forecast for key thin-film technology production to 2012.

Up to now, the solar generating field has been dominated by polycrystalline silicon photovoltaics that are less expensive to make but also much more limited in their geographical applicability because they do not conduct light.

The adoption of rotating cylindrical magnetrons by thin-film manufacturers for the majority of required deposition materials and process steps is demonstrating the potential to significantly reduce thin-film manufacturing costs by increasing throughput by 10% to 20%, reducing downtime for changing the target by 80%+ and nearly doubling target material utilization to between 70% and 80%.

Traditional thin-film photovoltaic manufacturing

Thin-film photovoltaics are produced by sputtering or depositing a thin metal film such as indium tin oxide or aluminium zinc oxide onto a substrate such as glass. The sputtering process takes place in a vacuum chamber that contains the target consisting of the material to be deposited as well as the substrate. Argon is introduced into the chamber and ionized. The target material is maintained at a

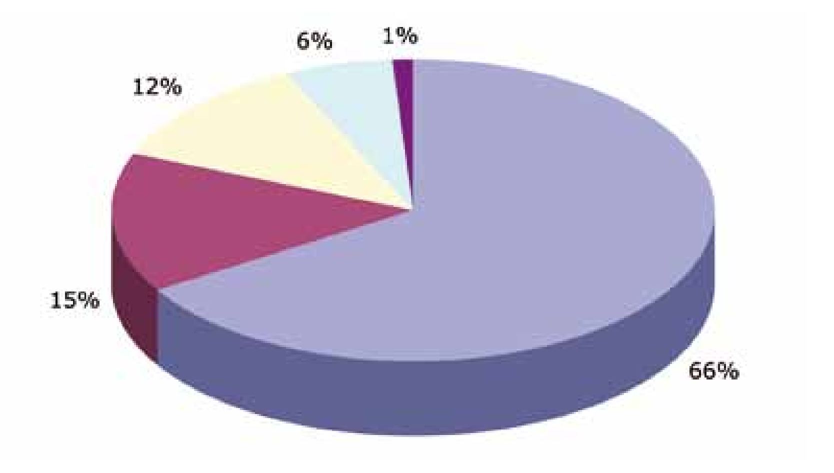

Figure 1. The Prometheus Institute: module fabrication volumes forecast to 2012 (MW).

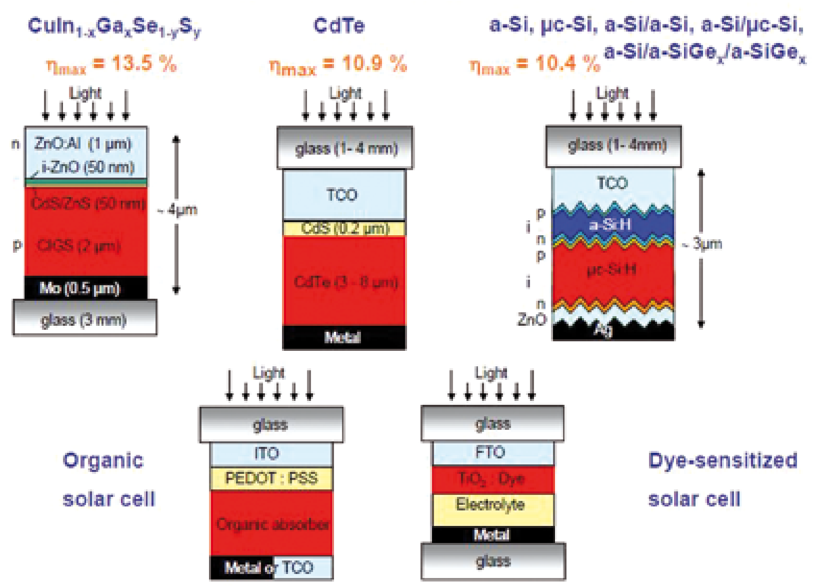

Figure 2. Typical variety of materials and cell structures used in thin-film technology. Many steps - such as TCO – require sputtering for correct deposition.

negative potential. The positively charged argon ion accelerates towards the target and strikes it with sufficient force to remove material.

The traditional approach uses a planar magnetron cathode. The weakness of this approach is that the usable volume of a planar is limited – a typical 5-inch by 20-inch by 0.5-inch planar target has a volume available for sputtering of about 50 cubic inches. Magnetic fields do not cover the entire target surface so some areas of the target are exhausted while others are barely touched.

> "Low utilization rates may be acceptable for pilot production levels but in a volume environment, targets become exhausted very quickly."

The utilization of a target by a typical planar magnetron is limited, according to Mark Bernick, President of Angstrom Sciences, Inc. "Even the most high performance linear arrays today typically only get in the 40% to 45% target utilization range, and that is with static magnets, which is typical for flat planars. With cylindrical rotating targets you can eliminate the trenching effect and utilize much more of the target. This equates to 2x utilization and 3x the area in the same tool footprint, so you gain 5x the efficiency."

Low utilization rates may be acceptable for pilot production levels but in a volume environment, targets become exhausted very quickly, requiring the line to be shut down periodically, reducing productivity and raising production costs.

Although there are inherent limitations with planar targets, this has not led to the technology's being omitted from thin-film PV manufacturing. Its lower up-front purchasing costs and widely understood parameters have been used for many R&D experiments and pilot production requirements. Furthermore, depending on the materials being deposited and their processing barriers, planar targets are being used in volume production.

"Unfortunately with some materials, providing them in tubular form is technically problematic," noted Bernick. "Some companies have retained planar targets and accepted that they will use several more planar targets compared to one cylindrical due to bonding material difficulties. Most metals are fine, though ceramic materials can be a problem."

Christopher Mihill, Managing Director of Testbourne Ltd., noted that some customers have retained planar targets for volume ramp due to the material challenges presented, even though they know the cost impact. "At the moment the material being used by the customer cannot be pressed into a rotatable shape."

> "The utilization of the target in a rotating cylindrical magnetron is considerably higher than a planar magnetron because rotating the target through the magnetic field assures that all areas of the target are eroded (exhausted) simultaneously."

Advantages of rotating magnetrons

Productivity and cost concerns are being addressed by a new generation of rotating cylindrical magnetrons that offer significant advantages over planar magnetrons. According to Angstrom Sciences, a typical rotating cylindrical magnetron with a 5-inch outside diameter, 4-inch inside diameter and 20-inch length has an available target volume of 108 cubic inches in the same footprint as a planar magnetron.

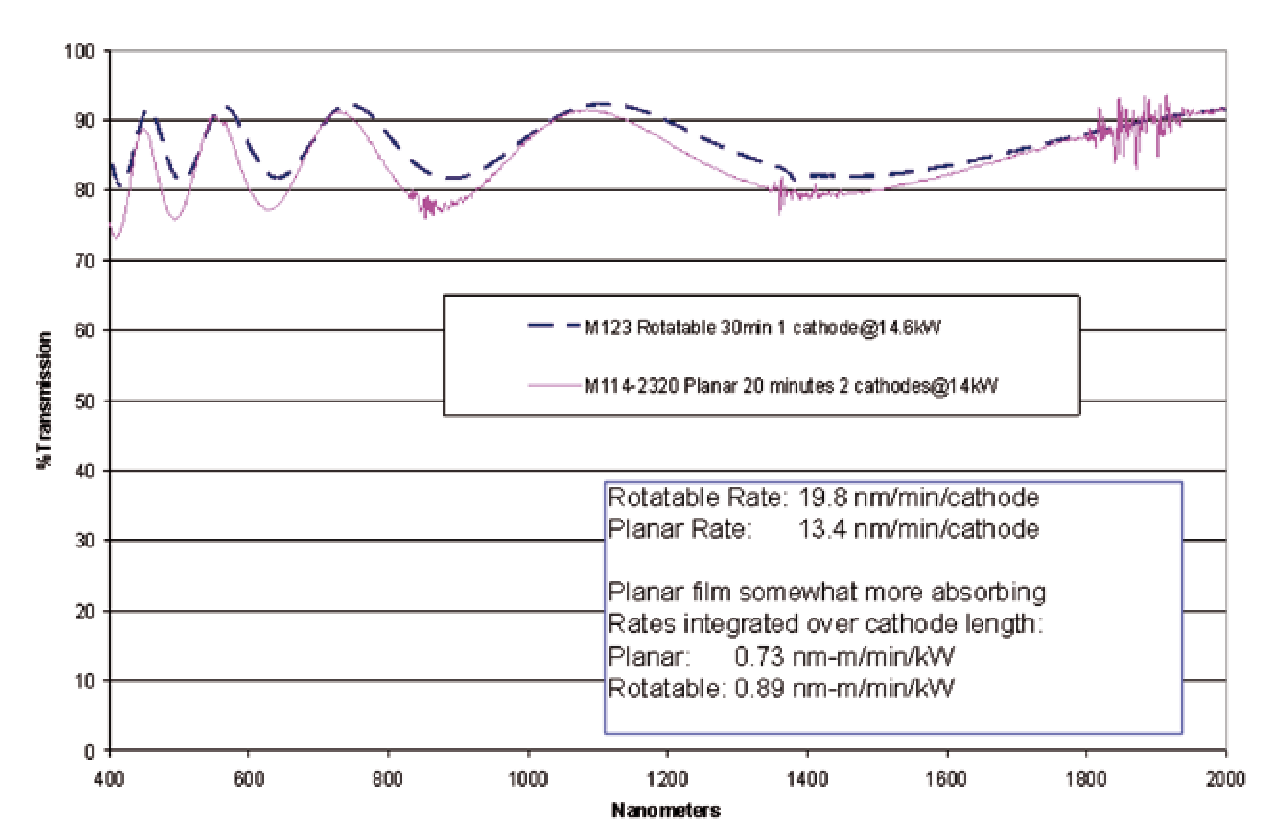

Figure 3. Rotating magnetron improves deposition rate by 10% to 20%.

The ability to fit more target into a given footprint is important given that processing is performed in a vacuum chamber and increasing the size of this chamber is very expensive. More than doubling of the target volume in the same space reduces downtime by increasing the interval at which the target needs to be replaced.

The amount of material in the target that can actually be used is limited by inevitable non-uniformities in the magnetic field used to direct ions to the target. The utilization of the target in a rotating cylindrical magnetron is considerably higher than a planar magnetron because rotating the target through the magnetic field assures that all areas of the target are eroded (exhausted) simultaneously. The best rotating magnetrons, according to the suppliers we surveyed, have a utilization rate of approximately 80%.

The increase in the amount of target material that is available for sputtering increases the sputtering yield as shown in Figure 3. The effective available target volume in a planar target is 50 cubic inches times 40%, or about 20 cubic inches. On the other hand, the effective volume per rotatable target is 108 cubic inches times 80%, or about 86 inches. This means that one rotatable target will last more than four times as long as a planar target resulting in a substantial reduction in downtime for changing targets and a resulting improvement in throughput. While the material in the target that is not utilized may be reclaimable, the vast majority of the cost of the target is involved in forming and bonding rather than material costs. The improvement in utilization provided by a rotating cylindrical target substantially reduces target costs.

Figure 4. Von Ardenne dual magnetron system.

John Madocks, Founder and President of General Plasma, Inc., noted other advantages to rotating cylindrical targets. "They also give you tremendous opportunity to cool the target as the heated zone is constantly moving away from the plasma. This enables the operator to turn the power up on the target to improve the rate of deposition. Something in the range of 10x the power density over planar can be used."

In a hypothetical planar configuration to match cylindrical target productivity, Madocks noted that such a situation would require 10 cathodes, a corresponding number of power and gas supplies all within the traditional chamber size. Adding more rotary magnetrons into the chamber boosts productivity further.

Optimizing the deposition profile

Electromagnetic simulation has been used to optimize the deposition profile of rotating magnetrons to reduce the debris landing on shields and potentially on the substrate. Figure 5 shows the typical magnetic field generated by a rotating magnetron. The magnetic field lines are largely focused off to the side, indicating that much of the target material will be aimed sideways at the shields rather than at the substrate.

> "The vast majority of the cost of the target is involved in forming and bonding rather than material costs."

Figure 6 shows how this field was improved by using electromagnetic simulation to optimize the geometry of the magnet. The field now points much more perpendicular to the substrate. In Figure 7, the blue line shows the typical deposition profile for a single rotatable magnetron while the red line shows the optimized deposition profile. The rotating magnetron with the optimized geometry can reduce the amount of debris landing on the shields and on the substrate by 33%.

The improved utilization offered by rotating cylindrical magnetrons also helps reduce the potential problem of re-deposition. Re-deposition is caused when the target material is deposited upon the un-eroded areas in the target. This re-deposited target material is poorly adhered to the target so over time it can break loose and fall onto the substrate causing contamination and potential quality problems. Cylindrical magnetrons greatly reduce the risk of re-deposition because the un-eroded areas are smaller and are completely off the substrate quality area.

Boosting performance

With some key inherent advantages offered by rotating cylindrical magnetrons, limitations do exist in boosting target utilization further than 80%. Although work would seem to be ongoing in tweaking these numbers, Madocks from General Plasma in particular cautioned over higher utilization claims.

"There is a lot of talk about achieving as much as 90% utilization rates; however this can confuse customers. The ability to add slightly more material at the ends of the cylinder would boost overall utilization of the target, but the trade-off is uniformity. It is therefore a balancing act between racetrack performance and uniformity which in itself could impact overall productivity of the line due to yield issues."

There would also seem to be little advantage in moving to higher purity materials. The consensus would seem to be that material purity levels currently supplied for sputtering are more than adequate.

Though reluctant to discuss the areas available to boost target performance, suppliers are continuing to develop the technology further, especially in the area of material density deposited, which can in turn boost cell conversion and yield levels. While not all material layers require thickness reduction for cell efficiencies, small gains in material cost reduction could be advantageous.

Koen Staelens, Product Market Manager at Bekaert Sputter Products, believes that intensive R&D efforts, as well as the in-depth understanding of customer applications that has come about via the company's being able to supply sputter hardware and targets, has pushed the performance barriers.

"We are often in a unique position to understand a customer's material requirements by first undertaking in house testing as well as the engineering to obtain the best solution via customization," commented Staelens. "We are also continually improving the hardware such as magnet bars for different materials and thicknesses. Improving reliability is also undertaken to improve the length of the coating runs. On the material front, we are constantly looking for new materials to boost density of the layers."

Volume production

The expected ramp of multiple large-scale thin-film facilities in the coming years could generate bottlenecks in the material supply chain, not least in sputtering targets, especially with an emphasis on using rotary targets.

The clear consensus amongst the suppliers interviewed was that raw material supply would not be an issue, and that the suppliers would be able to ramp production of targets to meet that demand.

Testbourne's Mihill characterised this confidence by noting that "although many thin-film companies are currently at low manufacturing levels, a particular customer is expected to require 600 to 1,000 targets as they ramp and between 4x and 8x that number in the future. We don't see any problem in matching that kind of requirement when it materialises with additional production lines for the targets."

"Though intrinsic limitations exist, there is a significant advantage associated with rotary magnetron technology over planar technology for thin-film manufacturers' ramping capacity."

Another benefit to thin-film manufacturers ramping is the cost reduction expected from lower material costs for target making as the economies of scale become significant. This will in turn enable suppliers to reduce the cost of targets over time, further helping to reduce the cost-per-watt.

Conclusion

One of the key factors in increasing the penetration of thin-film photovoltaics is reducing manufacturing costs. Rotary magnetrons have demonstrated their ability to substantially reduce thin-film photovoltaic manufacturing costs by increasing deposition rates, reducing downtime and reducing target cost. Though intrinsic limitations exist, there is a significant advantage associated with rotary magnetron technology over planar technology for thin-film manufacturers' ramping capacity that benefits should be realised over a long period of time.

"This technology [rotary magnetrons] can play a major role in helping thin-film photovoltaics achieve their full potential to increase the supply of renewable energy at an affordable price," concluded Angstrom Sciences' Bernick.

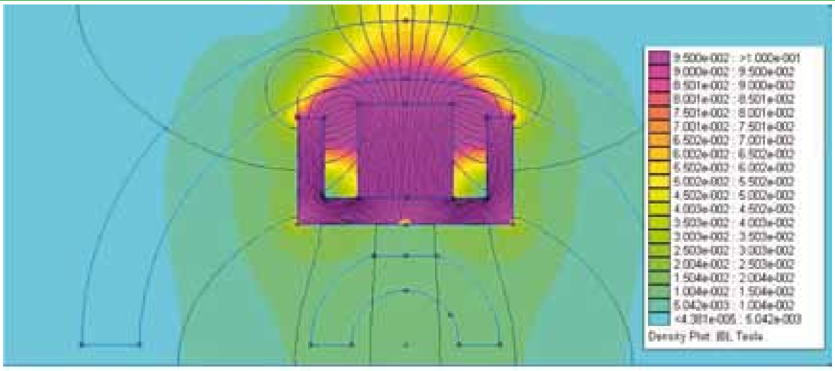

Figure 5. Electromagnetic simulation of rotary magnetron without optimization.

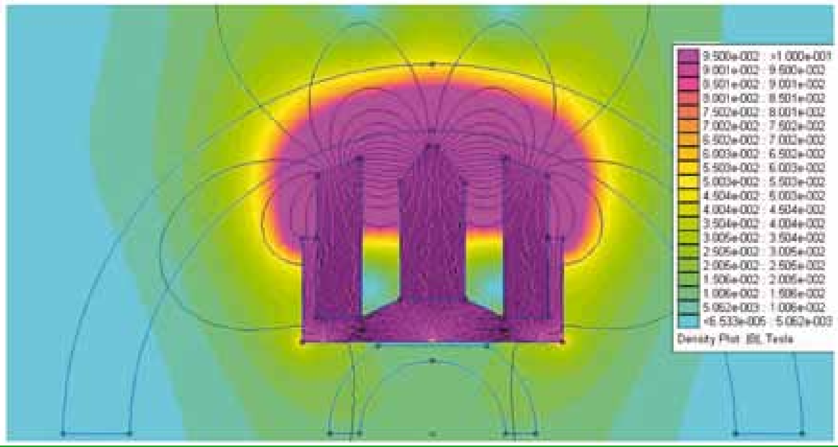

Figure 6. Electromagnetic simulation of rotary magnetron that has been optimized to improve the erosion profile.

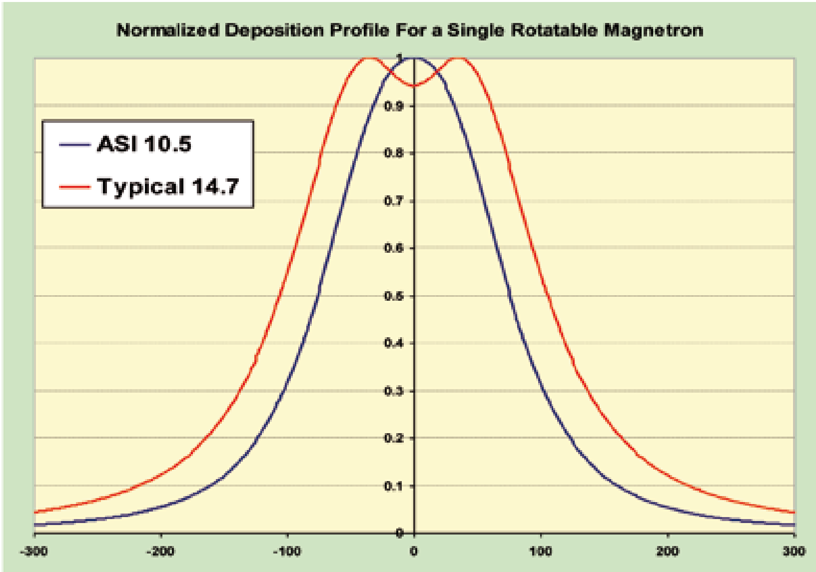

Figure 7. Rotary magnetron with optimized fields (blue line) directs more target material at substrate than un-optimized rotary magnetron (red line).

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About the Author

Mark Osborne is news editor for *Photovoltaics International* and has been covering the semiconductor and related industries for over 10 years.