Thin-film CIGS starts to come of age

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ABSTRACT

The next two years will be crucial in determining the market viability and future of what many see as the most promising thin-film photovoltaics technology: copper indium gallium (di)selenide (CIGS) and its gallium-free cousin, CIS. With potential conversion efficiencies just below that of crystalline silicon PV, low-cost manufacturing strategies offering a chance to reach sub-dollar-per-watt manufacturing costs on both glass and flexible modules, and applications ranging from utility- and industrial-scale farms to building-integrated commercial and residential uses, the quaternary compound has a large grid-parity upside – if the very real challenges of scaling production to commercial volume can be met.

A handful of companies – Showa Shell, Honda Soltec, Wurth Solar, Global Solar, and Sulfurcell – have already produced megawatts of cells and modules and are adding manufacturing capacity. Dozens more firms are in various stages of development, attempting to fine-tune the process as well as fit out and qualify pilot lines and volume-production-scale facilities by 2009/2010 and ship product as soon as possible.

Large technology companies have also entered the CIGS arena, directly or indirectly through investment, as evidenced by IBM and TOK's wide-ranging materials/process/tooling joint-development effort and Intel Capital's investment of US$38 million (as part of a US$135 million equity funding) in Berlin-based Sulfurcell's manufacturing expansion. If all of the promised fab ramps take place successfully and come online by 2010/2011, nearly 2.2GW of CIGS capacity (including Showa's proposed 1GW plant) would be available, according to the most recent estimates from the U.S. National Renewable Energy Laboratory (NREL).

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As for the markets, in its most recent report and forecast on thin-film PV, NanoMarkets foresees the total segment reaching US$8.9 billion in 2012 and US$22 billion in 2015 (a nearly 10x increase from 2008's US$2.4 billion), with the CIGS sector accounting for US$1.4 billion and US$4.9 billion (a more than 31x increase on 2008's US$152 million) in those respective years (see Figure 1).

Industry experts agree that several issues must be resolved in order for reliable, cost-competitive CIGS-based solar modules to be developed and proliferate:

- Module efficiencies must move beyond the low-double-digit range
- The toolset for growing the absorber films should be standardized and the manufacturing performance level improved
- The layers themselves should be thinned below a micron and columnar structures deposited by alternative methods need optimizing to achieve higher efficiencies
- A good, relatively cheap barrier layer to encapsulate flexible modules from moisture ingress must be perfected; and
- CIGS' absorber film uniformity and stoichiometry has to be improved over large-area substrates.

The U.S. connection

Nowhere have CIGS startups raised the hopes of investors and the solar-curious public more than in the United States, where TFPV (largely thanks to First Solar and Uni-Solar) accounts for more than 60% of solar production. Nanosolar, Miasolé, HelioVolt, Solyndra, SoloPower, Ascent Solar, and DayStar have raised (and burned through) hundreds of millions of dollars (largely via venture capital, private equity, initial public offerings, and government research awards), while others like ISET, RESI and Telio Solar have kept a lower profile.

These companies' proprietary CIGS absorber-layer deposition techniques, examples of which range from sputtering (Miasolé, DayStar) to electrochemical deposition/plating (SoloPower), and coevaporation on flexible polymer (Ascent) to nanoink printing combined with rapid thermal processing (Nanosolar), are unproven in terms of their ultimate scalability. None of these CIGS upstarts, whether they employ a discrete or monolithic approach to cells, has yet to truly demonstrate high-efficiency, high-yield, high-throughput multimegawatt-scale production capabilities remotely comparable to the thin-film sector's champion First Solar – despite the marketing hyperbole and assurances of great progress by some players.

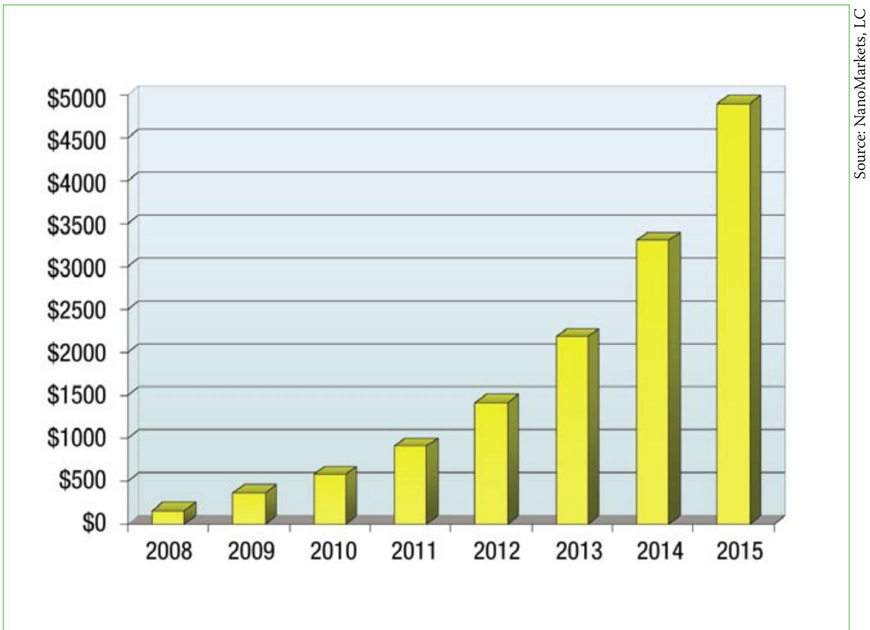

Figure 1. CIS/CIGS thin-film PV market, 2008-2015 (US$ in millions).

From Nanosolar's as-yet-unconfirmed claim of a 430MW manufacturing line to the stated goals of HelioVolt, SoloPower and the other aforementioned outfits of having 20, 25 or 40MW factories up and running by this year or next year at the latest, the pressure is mounting for CIGS companies in the United States and elsewhere to demonstrate their ability to make the scaling transition from the development line to the volume-production fab.

Solyndra, Miasolé making progress

According to Harin Ullal of NREL (where many of the thin-film technologies have been developed), of the 40 or so emerging and established CIGS companies that exist in the world that are actively developing and/or manufacturing CIGS worldwide, about 20 of those are located in the United States, including several operating in 'stealth mode.' Among the development-stage firms, he believes that Solyndra and Miasolé have 'made some real progress' lately in getting their TFPV to market.

Although Solyndra still refuses to publicly comment about its roadmap or core technology (which a patent search reveals as thermal coevaporation) – or much of anything else about itself, for that matter – two hefty five-year (2008-2012) module supply deals with Phoenix Solar and Solar Power, Inc. worth €450 million and US$325 million, respectively, were announced in July. This news suggests that the Fremont, CA-based company has made significant headway on ramping its manufacturing and may be moving close to product commercialization – or at least that the two customers believe it has.

> "For Miasolé, over the next 6 to 12 months, it's about execution."
> **Joe Laia, Miasolé**

Along with recently securing tens of millions of dollars in fresh funding from steelmaker/mining concern ArcelorMittal's new cleantech fund, Leaf Clean Energy, and other investor groups, Miasolé said in July that it had achieved a verifiable 10.2% conversion efficiency at NREL on its flexible cell-encapsulated glass modules that came off its nascent production lines in Santa Clara. (By comparison, the national lab's latest champion CIGS cell-on-glass recently reached 19.9% efficiency; Ullal says the ultimate theoretical efficiency for CIGS, regardless of substrate, might be as high as 27%.)

"This demonstrates our ability to consistently produce high-efficiency CIGS modules on production equipment," said President/CEO Joe Laia at the time of the announcement. "This is a critical step on our path to producing low-cost solar modules in high volume."


Photos courtesy: Global Solar.

Figure 2. Global's CIGS tools use a multisource coevaporation process.

Laia, a semiconductor capital equipment veteran who joined Miasolé in September 2007, told *Photovoltaics International* during a midsummer facility visit that the company has sharpened its focus in its drive to commercialization and unsubsidized 10-cents-per-kilowatt-hour grid-parity solar energy costs. "For Miasolé, over the next 6 to 12 months, it's about execution. I think you need to demonstrate the technology, that you can take the technology that you have and make a compelling product at a compelling price. There's no magic in any of this... For us, where we are in our development, we need to drive the efficiencies that we want and then go look for costs to take out."

Laia would not go on the record with many specifics of the company's manufacturing technologies, latest conversion efficiency distributions (tight as they are), factory ramp, or product shipment timelines. "We are in the process of demonstrating that we understand how to make material in a reproducible fashion that is commercially viable, but we aren't going to explain what those [details] are because I'd just be giving roadmaps to all the other guys in the space."

> Global Solar will have 175MW of capacity by 2010, if all goes according to plan.

During a tour of Miasolé's production floor, the activity level was high and the noise around the two U-shaped 20MW continuous roll-to-roll manufacturing lines was loud, largely because of an air-system connected to the handling system

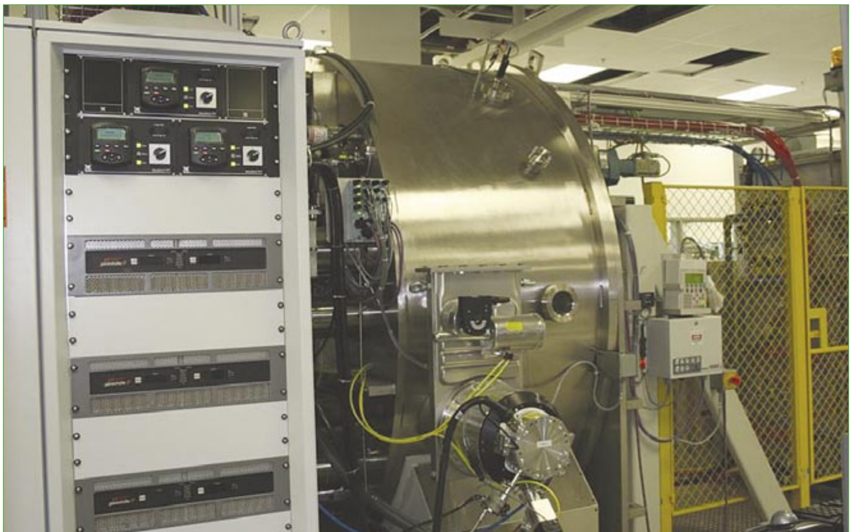

Figure 3. Large chambered systems sputter the TCO films.

on the toolsets. Kilometre-long spools of metre-wide steel foil are fed at a few feet per minute into the equipment, which are essentially multichamber cluster tools incorporating each of the steps required to process CIGS cells.

The flexible substrate, which is reoriented from a horizontal to a vertical position at the start of the run, rolls through the sequential process stages, including the standard molybdenum back-contact step, the proprietary 'cylindrical rotary magnetrons' sputtering the CIGS, and the deposition of the cadmium-sulfide buffer layer and then the transparent-conducting-oxide (TCO) front-electrode film.

"It's steel in and CIGS out," as Laia explained, a single-pass, "end-to-end manufacturing process." The material-laden foil is then laminated, cut into cell strips, tested, and binned for integration/encapsulation into glass PV modules being assembled elsewhere in the factory.

Global Solar ramps capacity

When NREL's Ullal speaks of "the established guys," that is, the companies employing one of the two working CIGS processes (thermal coevaporation and two-stage vacuum-coated precursor/selenization or sulfurization) and shipping commercial modules in relative volume with efficiencies ranging from 10-12%, the only U.S. company to make the senior project manager's short list is Global Solar.

Global uses a batch serial process on its roll-to-roll production lines.

With 40MW of manufacturing capacity coming online at its new 110,000-square-foot factory in the desert south of Tucson, AZ, a 35MW plant ramping near Berlin, and another 100MW scheduled to fill out the main site by early- to mid-2010, the company will have 175MW within two years, if all goes according to plan.

Thousands of strings of flexible thin-film 210mm long x 100mm wide CIGS cells on foil from Global's new lines have been shipping down the road to Solon America's nearby assembly facility (itself in a ramp-up to an eventual capacity of 80-100MW), where they are packaged in 'tech-agnostic' glass modules alongside the units containing crystalline-silicon-based cells from other manufacturers.

Global is not exactly a newcomer to the space, with roots stretching back to Martin Marietta's early CIGS efforts in 1991 and an official birth year of 1996, when it was established as a joint venture between ITN Energy and Tucson Electric. For the first 10 years, the company worked on researching and developing flexible plastic CIGS panels, first for military and government use and then for Brunton and others in the commercial and consumer markets. It built a 4MW factory in the early 2000s, steadily improving efficiencies and yields, and driving down costs, while shipping large amounts of the portable power units.

Figure 4. One screen printer at Global can handle 40MW of capacity.

When Solon and a private European investor bought Global from then-owner UniSource in 2006, the resulting capital infusion allowed the company to start planning its first volume production facility and also optimizing a novel approach to engineering its CIGS cells into traditional glass panels – a process now in manufacturing at Solon.

Global's factory floor

During a late April tour of the Tucson facility, Global's Chief Technology Officer Jeff Britt walked around the floor and described the manufacturing flow. The factory floor was bustling with equipment in various stages of delivery, installation, characterization, and optimization, with plenty of floorspace still remaining for the later phases of expansion.

"We have put our own IP stamp on how to control the selenium."
Jeff Britt, Global

Although Global operates roll-to-roll production lines, the web material does not feed continuously through one, large multichamber vacuum process system, but rather the spools move from tool to tool in what Britt called a "batch serial process." Ceiling-mounted cranes lift the heavy foil rolls off the tools and place them on carts, which are then pushed to the next equipment set in the process flow.

By taking this not-exactly-continuous roll-to-roll approach, "it allows us to balance our production," explained Britt. "If you have to make an improvement in one process that allows you to speed the web up, all of a sudden everything else is a bottleneck. You can buy particular toolsets as you increase the capacity of each process; you can put in particular tools to even out and eliminate any bottlenecks in the production process. It frees you to do that kind of development that can be implemented immediately instead of having to wait for the next entire generation of tools to come out, offering flexibility in your capacity ramp."

Processing the CIGS

The two- to three-thousand-foot-long rolls of foot-wide, 1mm-thick stainless steel foil are loaded first onto a custom-designed sputtering tool, four of which will be part of the initial 40MW ramp. The process starts with the deposition of a thin chromium layer to promote better adhesion to the foil of the 300-400nm molybdenum films deposited by the same tool. Britt said the per-roll cycle time in the moly tool is about eight hours, including the pumpdown, deposition, venting, and cleaning steps.

The big rolls of foil then move the key process sequence – the multisource coevaporation tool used to deposit the 1.5-2.0μ-thick layer of copper, indium, gallium, and selenium, where the web is heated up to between 500 and 600°C. "We need more of these tools than the Moly tools," Britt noted. "We don't have exact matching, where one process matches another in terms of capacity, so we've got an unbalanced number of systems." Eventually, seven pieces of CIGS equipment will extend the length of the factory floor, separated by a pumphouse chase, according to Britt.

Regarding one of the trickiest pieces of taming the CIGS process – the control of selenium when the temperatures get too high – Britt said, "we have put our IP

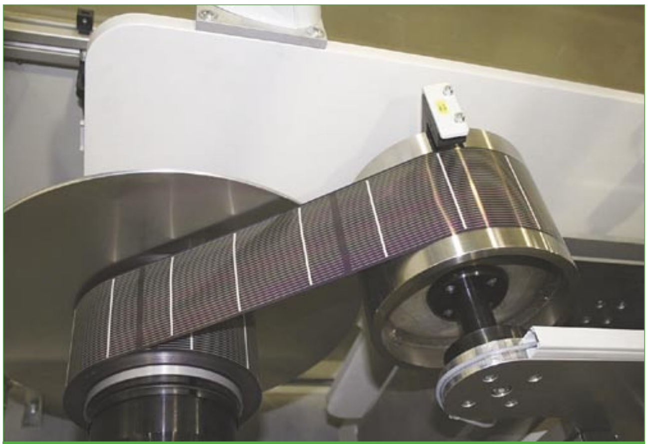

Figure 5. Up to 18 CIGS cells are strung together at a time at Global.

stamp on this on how to control the material. Because it has a high vapor pressure, it's difficult to supply selenium in the right way to lead to a high-quality, high-efficiency solar cell. You induce defects if you don't control the selenium properly."

After the CIGS films are deposited, the web moves over to the cadmium sulphide coating systems, which lay down the thinnest film (at 80nm thick) in the stack. The proprietary process tools are segregated inside an atmosphere-controlled room of their own, "because of some of the process by-products need to be controlled to remove hazardous materials," explained Britt. "The process generates some level of cadmium in liquid form. We have an entire waste-treatment facility behind the room, so that when this waste is treated it becomes entirely free of the heavy metal and we use the effluent from the abatement process to chill the towers of our air-conditioning system."

The rolls then are transported to the TCO sputtering equipment, which is a "relatively fast process," according to Britt. "We'll need only three tools of this type to round out our 40MW." However, he would not disclose the type of TCO film that is in use at Global.

'Looks a lot like a silicon cell'

With all of its thin-film layers deposited, the processed foil then moves to another part of the factory for screen printing. "This looks a lot like a silicon solar cell that has a screen-printed collection grid that is used to collect the majority of the current and funnel it out of the solar cell," he pointed out. "The rest of the room is one large curing furnace because this one printer services the entire 40MW plant."

> Global's Britt wants to see improvements in analysis and metrology tools.

As the oven for curing the silver ink laid down during the printing process needs to be very long, the unit goes to the end of the room, makes a turn, and winds back to the front of the room. Britt said they will add another system, with a similar layout, during the next expansion.

He held up a handful of printed cells on foil, showing how each pass prints a dozen of the cells. After printing, the next step is slotting the cells, where the roll of 12 is taken and "split it into three separate rolls. Now we're going to have a single roll of solar cells instead of three rolls wide. We do this so because that will be the input for the next system, which strings together those cells. You end up with something that looks like a roll of postage stamps." With the stringer, Global makes connected pieces of "up to 18 cells long, which, with wiring, is approximately 2 metres long."

From cell strings to module

The strung-up cells are then sent to be tested in the pulse simulator down at the other end of the area, "which measures efficiencies and power output characteristics of the string, and then lifts it up and places it into a bin. Depending on the power output, we have a number of bins and we'll sell those like-powered strings to one customer." More stringer tools will be installed, eventually stretching down the length of the building, Britt said.

Once the cells are tested, "we package them up and ship them out to whoever's going to make the modules," such as minority owner Solon. "Those modules will be subjected to very stringent reliability tests...we'll be qualifying them and making sure they'll live through that 20- or 25-year warranty that we're offering." One close-to-home, real-life test of Global modules will come from a 750KW solar field across the parking lot from the factory, scheduled to be activated in Q3 2008.

One area in which Britt would like to see some improvements is the available metrology and analysis gear. "We're always keeping our eyes open for new metrology tools that we can either integrate in-line or between processes, tools that will give us some early indicators. We feel right now that there's not enough information, we want to know more things about the morphology and the composition that we really don't know right now. You have to carry your yield losses around for a long time with this kind of process."

Figure 6. Global's PowerFlex strings can be integrated into standard modules.

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(Sources also included various background materials and press releases from CIGS companies' Websites, the NREL Website, and bits and pieces of other Chip Shots blogs).

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