Flexible CIGS thin-film PV establishes module manufacturing base, moves closer to BIPV market readiness

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This paper first appeared in the fourth print edition of *Photovoltaics International* journal.

ABSTRACT

Despite the low-cost, high-efficiency, radical form factor promise of many thin-film photovoltaic technologies, scaling these materials to large-volume production has presented a wide array of challenges. Because of the recent polysilicon shortage, an incredible amount of resources have been focused on this goal and many thin-film alternatives are now available. One of the most intriguing of these materials, copper indium gallium diselenide (CIGS), has great potential to reset the thin-film market and make new applications cost effective and viable. CIGS technology is differentiated from competing PV materials by a combination of factors. The manufacturing cost of thin-film cells can be very inexpensive since they require few raw materials and can be made with an efficient, scalable roll-to-roll process. CIGS has been established as the most efficient thin-film technology in converting sunlight into electricity. A flexible substrate will ultimately enable energy and building-integrated applications beyond the capability of rigid, heavier PV products.

Introduction

Global Solar Energy, a manufacturer of thin-film PV cells, has been able to scale up manufacturing capacity of CIGS on a flexible stainless-steel substrate to 70MW at production facilities in Tucson, Arizona and Berlin. The company's strategy has been to gain early entry to the market, attract dynamic technology partners, and leverage these partners' expertise to accelerate development of next-generation flexible CIGS systems.

The first step on this path has been accomplished by building on well-known module assembly methodologies established by silicon PV, specifically the tabbing and stringing configuration of cells and glass module encapsulation. By adopting these industry standards, significant technology hurdles have been bypassed and the kind of large-scale

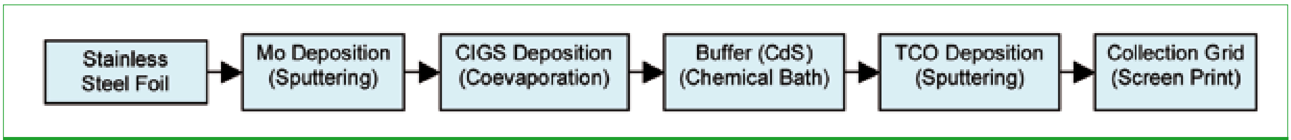

Figure 1. Flexible CIGS roll-to-roll manufacturing flow.

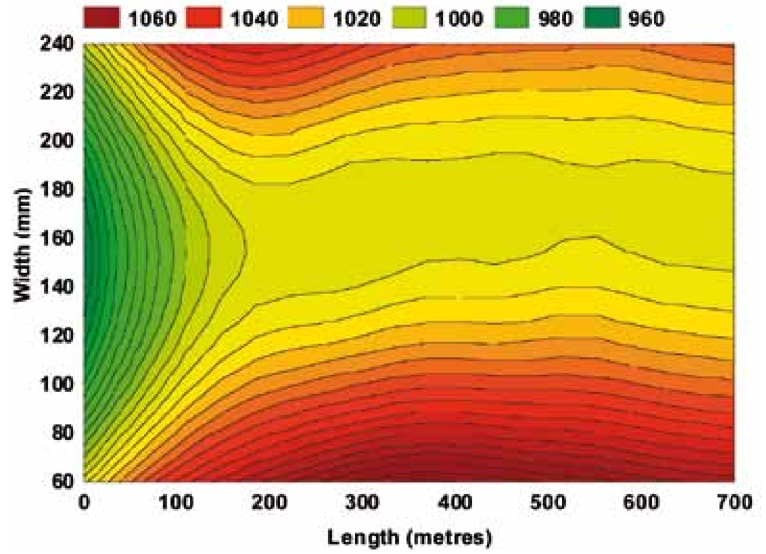

Figure 2. Contour plot of Mo thickness (a.u.) down and across the web as measured by XRF (distance weighted least squares fit).

Figure 3. Equipment for CIGS deposition by coevaporation.

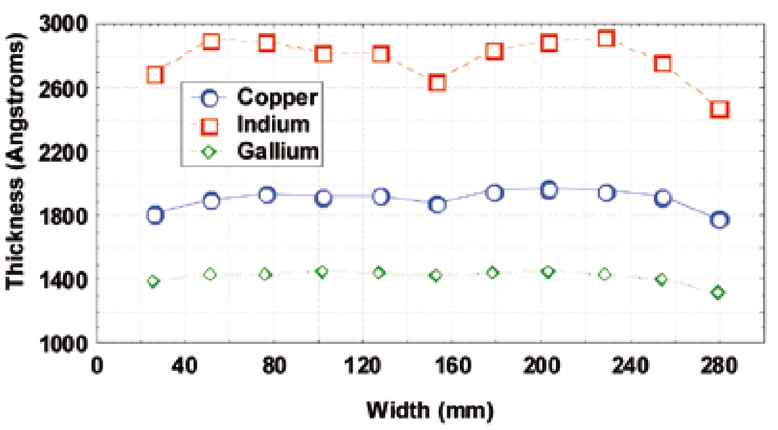

Figure 4. Equivalent thicknesses of copper, indium, and gallium in a CIGS film (across the web width) as measured by ex-situ XRF.

manufacturing base needed to be cost-competitive and to attract partners with critical expertise has been established. The company's 'strings' of CIGS cells are now being sold to glass module manufacturers for use in solar power fields.

Global Solar is working with several leading technology companies to address those 'bypassed technology hurdles' and implement its long-term strategic roadmap to bring to market a flexible, lightweight, high power-density photovoltaic solution for OEM product manufacturers. A flexible moisture barrier and integrated cell interconnection are the two critical technologies that the company believes will enable it to capitalize on these sustainable competitive advantages of CIGS thin-film technology. This article describes a flexible CIGS thin-film PV manufacturing process, the current product being manufactured in high volume, the technology developments being pursued, and the future market opportunities that will result from these efforts.

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CIGS manufacturing process

The company's manufacturing process can be broken into two distinct parts: material deposition and string assembly [1,2]. The first manufacturing segment emphasizes roll-to-roll processing, as shown in Figure 1. Cell size and shape are introduced at the end of the first manufacturing segment when the cell dimensions are defined by screen-printing a conductive ink 'collection grid' on the top surface of the PV material. At this point, the PV material is cut into cells and connected in series into 18-cell strings.

The material deposition processes follow a batch manufacturing flow using stainless-steel flexible webs up to 1000 metres long, one-third of a metre wide, and 25μm thick. Each web is processed independently through the coating steps. Since each web and mandrel combination weighs between 40 and 60kg, they are loaded and unloaded into the deposition tools by crane and conveyed between processes on carts.

Batch-style production decouples the optimization of the individual processes and the balancing of production flow. Each deposition process is independently optimized and production capacity bottlenecks can be addressed by adding additional tools. Multiple toolsets also provide redundancy to mitigate the impact of equipment downtime. Finally, batch production permits offline characterization between process steps for improved quality control.

Substrate and back electrode

The stainless-steel foil substrate was chosen over other options (polyimide film, glass, etc.) because it enables significant competitive advantages compared to other thin-film technologies and processes. The foil is relatively lightweight and flexible – valuable characteristics for emerging building-integrated photovoltaic (BIPV) applications. The stainless-steel substrate also allows the highest material processing temperatures, which help facilitate the best photovoltaic conversion efficiencies in CIGS. A stable platform for the deposition is provided by the foil's coefficient of thermal expansion, another critical factor in maintaining performance stability and product lifetime.

The back-electrode materials of chromium and molybdenum are deposited by pulsed-DC sputtering. The thin chromium coating enhances adhesion of the molybdenum, while the molybdenum protects the substrate and readily accepts

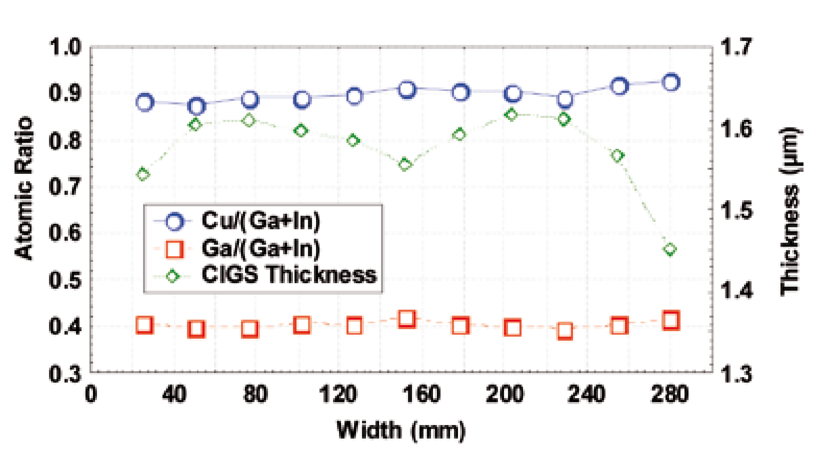

Figure 5. Atomic ratios and thickness of a CIGS film (across the web width) as measured by ex-situ XRF.

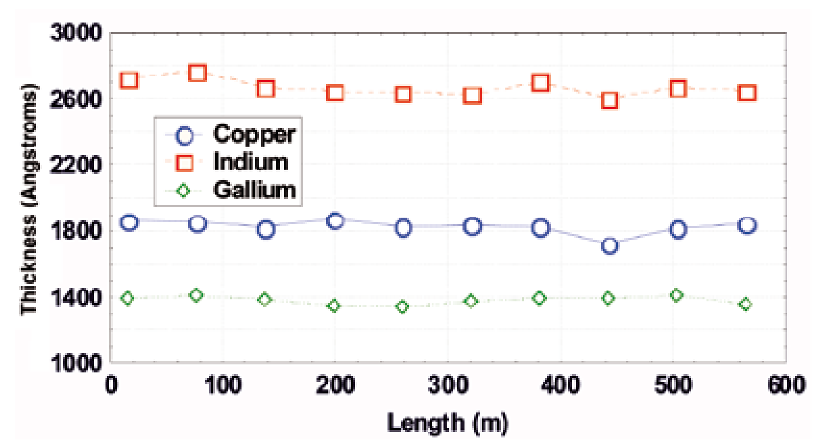

Figure 6. Equivalent thicknesses of copper, indium, and gallium in a CIGS film (down the web length) as measured by ex-situ XRF at the web centre.

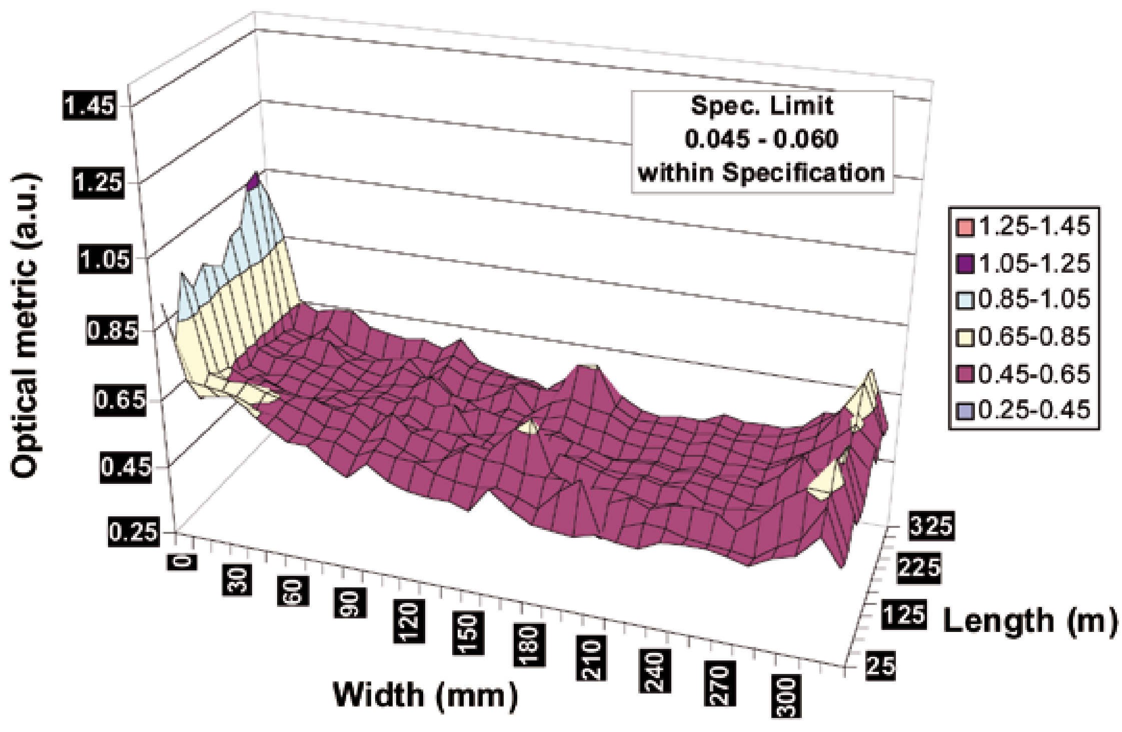

Figure 7. Optical confirmation of CdS coating thickness within specification down and across the web.

Figure 8. Front-electrode deposition by sputtering (a similar tool is applied for the back electrode).

the CIGS layer. The thickness of the back electrode is optimized for maximum performance and minimal cost [3]; the Mo coating thickness is characterized by XRF (Figure 2). Along the majority of the web length, the thickness uniformity is +/- 3%, and the thinnest coating occurs in the web centre and at the beginning of the web.

Absorber layer

CIGS is a direct bandgap material with good light absorption properties and a bandgap energy well-matched to the solar spectrum. This p-type semiconductor material has excellent long-term stability and has been called a "smart" or "self-healing" material because of its copper-related properties.

CIGS is deposited by multisource coevaporation of the elements (Figure 3). The effusion sources are loaded with the least expensive forms of the metals (shot, wire, etc.). In practice, the effusion source control reactivity is small because of the large thermal masses of the sources. The total deposition time for the CIGS coating, put down at a thickness of 1.7μm, is 2.6 minutes.

Coating uniformity of the copper, gallium and indium films, is critical to achieving optimal CIGS string performance and high yields. In practice, thermal evaporation cross-web uniformity is more difficult to achieve than uniformity down the web length. The cross-web CIGS uniformity is chiefly determined by the design of the effusion sources, deposition zone geometry (location of sources and shielding), and zone pressure. However, the new CIGS coaters and effusion sources have been designed with increased degrees of freedom to permit better control of coating thickness across the web than was allowed by the previous generation of coaters.

The cross-web profiles of the elements are similar for a typical CIGS film deposited in the new coaters, as shown in Figure 4. All elements are deposited from identical effusion sources in nearly the same environment, resulting in similar profiles. When combined to make CIGS, the thickness varies across the web width, but the composite ratios Cu/(Ga+In) and Ga/(Ga+In) remain relatively uniform (see Figure 5).

The coating uniformity of Cu, Ga, and In along the web length has been evaluated by XRF for CIGS-coated webs up to 670m

Figure 9. Collection grid printing system for CIGS cells.

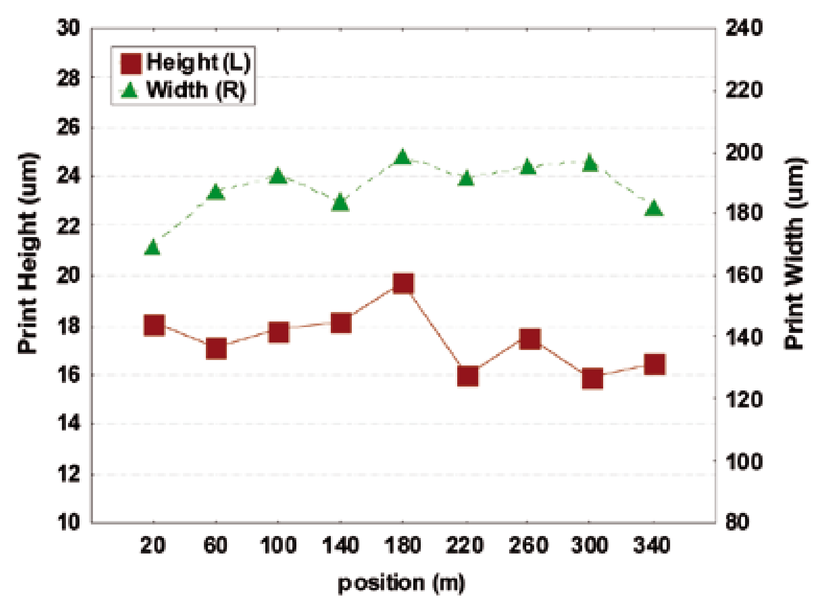

Figure 10. Collection grid finger average print characteristics along the web length.

in length (Figure 6). In this instance, the web was sampled at identical cross-web locations down the length of the web. The effusion sources contain relatively large charges of the elements. The large thermal masses provide stable evaporation rates within the response time of the control loop, and uniformity along the length of the web is generally excellent.

Buffer layer

The cadmium sulphide (CdS) layer, which acts as the 'n' part of the p-n junction that forms the PV cell, is deposited in a wet chemical bath. CdS and the deposition method used have diverse beneficial properties and are important factors in the manufacturing of a robust PV material.

Targeted CdS thickness is approximately 80nm. If the CdS coating thickness is less than optimal, open circuit voltage (V_{oc}) and fill factor are reduced; in much the same way, if the coating thickness exceeds the optimal value, short circuit current density (J_{sc}) is decreased because of increased absorption of light within the CdS coating.

A non-destructive optical technique (see Figure 7) has been developed for qualification of the CdS coating thickness on production webs. The characterization is performed after the CdS has been applied on the CIGS coating, and prior to the deposition of the TCO coating. The CdS coating thickness is typically within specification in the utilized portion of the web, as web edges are not utilized. In addition, the CdS process effluent is treated by a purification system to reduce metals and other contaminants levels below those considered hazardous, with only solid waste generated.

Front electrode

A transparent and conductive layer is sputtered onto the top surface of the photovoltaic material and acts as the front electrode for the device, allowing electrical contact to the device, acting as the current collection layer and also stabilizing and protecting the semiconductor layers below. The TCO, an n-type material that complements the underlying CdS n-type buffer coat, is deposited by a pulsed-DC sputtering tool such as that featured in Figure 8. The total TCO coating thickness is approximately 100nm.

Collection grid printing

The final deposition step – the screen-printing of a conductive grid – serves as the collection circuit for the photoelectrons that have reached the cell surface, which in turn defines the cell dimensions and the contact areas for the ribbons used to assemble the strings. The area where the web is cut to create the individual cells is not coated with ink; if this happens, there is a strong probability that the ink will be smeared through the cut layers and create a short between the top and bottom layers of the PV cell.

The collection grid is formed by roll-to-roll screen-printing of a silver ink (Figure 9), which is thermally cured in the same step, prior to rewrapping the web. The nominal cell dimensions are 210 x 100mm, with three cells printed across the web's width.

Designed to minimize resistive losses, cell shading and required silver ink volume, the collection grid's first order of business is the determination of the design targets – a task that can be achieved through proper screen design and tool setup. However, other variables such as inkpot life, screen wear and environmental conditions can push the process out of control. Resistive losses can be severe if the grid fingerprint geometry deviates substantially below the design goals for height and width. Excessive ink application can also add unnecessary product cost.

The ink-print process has been characterized by optical profilometry, in which process cells are extracted at intervals from a single printed reel 350m in length, and the grid fingerprint height and width are characterized at two locations on each cell. The mean ink height and width down the web has been determined to be within acceptable limits (Figure 10).

Web slitting

The last step before the string assembly process is the slitting of the completed webs of photovoltaic material. The initial 300mm-wide stainless-steel rolls have been processed through sputtering, evaporation, and plating operations. As noted earlier, one key challenge of high-volume manufacturing of CIGS thin-film material remains the deposition uniformity, especially in the cross-web direction. Variation of film uniformity across the short dimension of the roll can greatly impact the ultimate cell, string, and module performance.

To minimize the impact of this type of uniformity variation, the rolls are slit lengthwise into three reels, as illustrated in Figure 11. Each reel is 100mm in width (one cell wide) and 1000m in length. Slitting in this direction significantly tightens the range of film variation within the reel, which in turn directly transfers to a tighter distribution of cell performance within each string. When the cells are attached in series, the net performance of the assembled string is affected by the performance of the poorest cell. So, by matching cell performance as closely as possible, the highest possible string performance – and ultimately, module performance – can be achieved.

Tab and string

At this point in an analogous crystalline-silicon process, the PV material would be supplied as cells to the module manufacturer, which would feed the cells into a tabber-stringer system at the front end of the process flow. The tool would construct series-connected strings of Si cells using commercially available equipment, process recipes, and materials.

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For flexible CIGS PV material, however, there is no industry-standard stringing solution available. To address this obstacle and offer module manufacturers a 'drop-in' replacement for silicon cells, the stringing process has been integrated into the company's manufacturing capability. This stringing solution leverages the Si cell tabbing and string configuration and automated equipment technology as the shortest path to market for CIGS cells.

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Product description

The primary product is an 18-cell PowerFlex solar string, a configuration designed as a 'drop-in' replacement for crystalline silicon photovoltaic strings that allows the CIGS thin-film technology to leverage the well-known encapsulation methods and tools used by the established module manufacturing base. This product is being marketed and sold to Solon and other PV module manufacturers for deployment in utility-scale power field projects.

Each cell is 100 x 210mm in area and can generate a nominal peak 0.4V, 5A, and 2.2W under standard test conditions. The power output of the 18-cell string is nominally 40W, depending on its net efficiency. The string assembly shown in Figure 14 measures roughly 1.8 metres long; the typical physical and electrical parameters of the string are summarized in Table 1.

Module construction

The module manufacturers commonly combine four CIGS strings in a traditional glass/PV/backsheet module construction. Although the string format may appear familiar to module customers, the material does require some accommodation. CIGS and thin-film string performance have been shown to be sensitive to moisture and environmental conditions, thus proper encapsulation is critical in achieving the longest possible product lifetimes.

Extensive material testing and module analysis have been performed to identify and validate CIGS-compatible module construction materials. This work has resulted in a module design that meets certification standards such as IEC 61646, "Thin-film terrestrial photovoltaic modules – Design qualification and type approval," based on tests conducted at the Arizona State University Photovoltaic Testing Lab. The company has also worked closely with equipment manufacturers to develop automated handling solutions that integrate the flexible CIGS strings into an existing module production line.

Applications

Utility-scale power generation

One of the largest CIGS power fields in the world sits adjacent to the company's Tucson facility. This 750kW DC field, which has been operating since November 2008, contains 6600 CIGS-strings-in-glass modules. The installation has been estimated to be capable of generating 1.1 million kWh of electricity annually for the nearby PV manufacturing plant. As Table 2 reveals, the actual field output has exceeded this rate by almost 25% over the first months of operation, demonstrating the viability and availability of CIGS-based utility-scale power generation.

The only significant solar plant design consideration for CIGS modules is making sure that the inverter has an adequate input voltage range. Since CIGS has a different fill factor and thermal coefficient than crystalline silicon, the inverter input voltage must incorporate a slightly broader range over possible operating conditions. Other field design elements such as site requirements, array support structures, sizing and wiring configurations, monitoring, and operations systems are mostly transparent to the CIGS cells and fall within industry standard practices.

Building-integrated photovoltaics

BIPV describes photovoltaic technology integrated into building materials to replace traditional roofing, shading, and façade products, with the goal of reducing material and installation costs and meeting the aesthetic requirements of building design. BIPV has the potential to become a mainstream technology if it can meet these market goals. As with most product technologies, the cost threshold is the critical factor that differentiates a mainstream product from a niche product. Solar America Initiative participant Dow Chemical, with its 'solar shingle' approach to packaging CIGS cells within a roofing material, is among those companies pushing closer to developing cost-conscious commercial BIPV products.

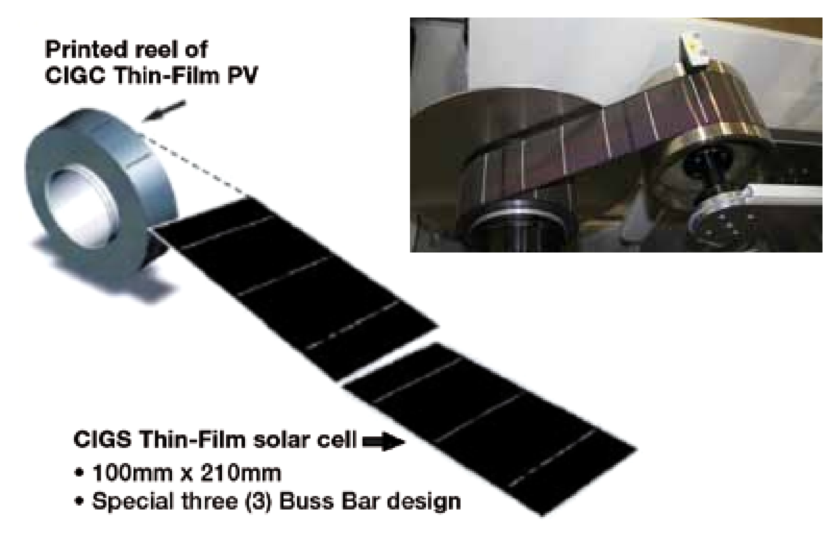

Figure 11. Illustration of printed reel of flexible CIGS thin-film PV.

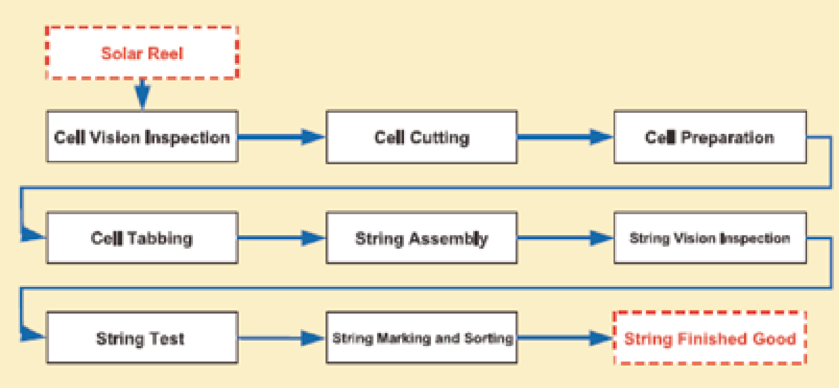

Figure 12. Tabber-stringer process flow for flexible CIGS thin-film PV.

BIPV products can leverage the potential of flexible, lightweight, high-efficiency CIGS technology to deliver:

- Lower installation costs. A flexible CIGS product will closely resemble the dominant roofing materials being used in the construction industry – composite asphalt shingles in residential roofing and roll membranes in commercial roofing. This will facilitate installation by the existing industry workforce without significant specialized training or additional manpower.
- Low manufacturing costs. Thin-film CIGS has the potential to reduce building product material and manufacturing costs to levels that will achieve grid parity and a competitive levelized cost of electricity (LCOE). This economic strategy requires efficient, high-volume, low-cost, automated mass production capabilities.
- Product aesthetics. Although not explicitly part of the cost equation,

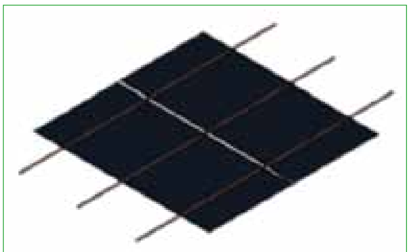

Figure 13. CIGS string and tab configuration (two-cell segment).

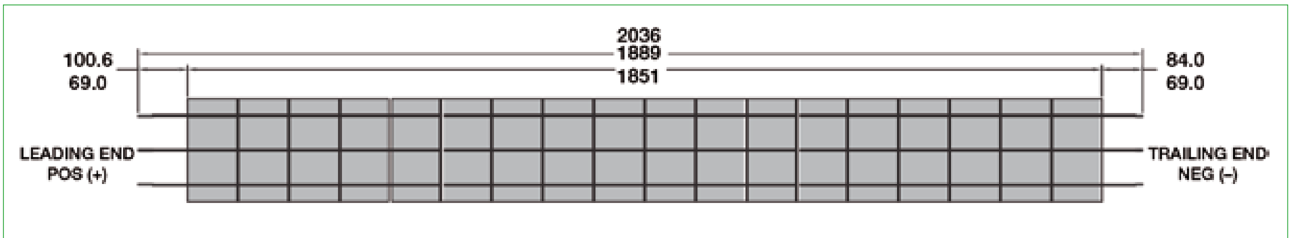

Figure 14. PowerFlex 18-cell CIGS string.

Parameter	18-cell String	Single Cell
Area (m^2)	0.39	0.022
Weight (g)	123	6.8
P_{max} (W)	39.5	2.2
V_{max} (V)	7.3	0.4
I_{max} (A)	5.4	5.4
V_{oc} (V)	10.3	0.6
I_{sc} (A)	6.7	6.7

Table 1. Typical physical and electrical parameters for 18-cell flexible CIGS string and single CIGS cell.

Solar Energy Generated		
Year	Month	Energy (MWh)
2009	Mar	124.37
2009	Feb	109.01
2009	Jan	110

Table 2. First-quarter 2009 energy output for Global Solar's Tucson CIGS thin-film PV module field.

aesthetics will be essential for demand generation as PV moves from the power field to the building market. Flexible CIGS can mimic traditional building material design forms to foster market acceptance and can fit into many applications where weight and conformal requirements limit the use of traditional silicon PV technologies.

Ultimately, CIGS PV has the potential to provide lower material costs and higher efficiencies than competing flexible thin-film technologies. Of these two factors, module efficiency stands as the most important consideration, since it is a nonlinear factor in the LCOE model.

Technology development

To enable CIGS-based flexible roofing and curtain wall products, ancillary technology solutions must be developed just as they have for the glass module. The key element needed for a 25-year BIPV product lifetime is a flexible moisture barrier that can replace glass. A natural starting point in the search for this film can be found in the OLED (organic light emitting diode) display development work that has been taking place for years. Many leading polymer companies have moisture barrier technologies that grew out of the OLED market and are being evaluated for solar applications.

Moisture barrier films have been sampled, test structures created, and thousands of hours of high-temperature (85°C), high-humidity (85% RH) screening tests performed. Existing encapsulation materials, such as ETFE, PET, and MET, have served as baseline controls capable of water vapour transmission rates down to 10^{-3}g/m^2 per day. One critical challenge in the evaluation of new barrier materials is that they have exceeded the detection limits of the industry's analytical methods used to measure their performance.

Most industry sources – including Fujifilm, which has developed an advanced "transparent super high barrier film" that can be deposited on various types of flexible base materials – believe a barrier level of 10^{-6}g/m^2 per day is needed to achieve the product lifetimes that will make BIPV products viable.

The accelerated DH test results are translated into product lifetime estimates by the compilation of lifetime data on flexible CIGS assemblies for many thousands of hours. These data are then compared in performance against the IEC-certified glass encapsulation baseline data. In the past year, there have been significant advancements in these barrier materials, and suppliers are beginning to plan for pilot production.

One company that has seen significant strides in this regard is DuPont Photovoltaic Solutions, claiming advances on such properties as transparency, ultramoisture barrier resistance, UV stability, and long-life durability on CIGS barrier materials for flexible BIPV applications, something it sees as a natural extension of its Teflon PV frontsheet product line.

To close the gap between commercially available vapour barrier performance and the level of protection required, on-going work also seeks to reduce the vulnerability of the CIGS assembly to the environment. The focus of this effort is development of new materials and methods of cell interconnection that are less vulnerable to moisture and have the additional benefits of being well-suited for roll-to-roll lamination and semi-customized product form factors. This work includes characterization under different environmental conditions of each CIGS cell layer and interface, as well as the materials and interfaces of the string assembly. GE Global Research has been actively engaged in analyzing the degradation kinetics of CIGS cells, and has come up with a model that will be used extensively to understand the tradeoffs between cell moisture sensitivity and package construction, as well as the ultimate impact on real-world lifetimes of various cell/package combinations.

Understanding the behaviour of the strings at this level has allowed material suppliers to accelerate development of new materials and solutions.

Conclusion

The presence of a flexible CIGS thin-film PV product in the market has attracted significant interest and enthusiasm from technology companies, which has led to the accelerated development of critical ancillary materials. As these new technologies reach commercial status and OEMs introduce new products, promising novel applications and new business models will become viable. High-performance flexible TFPV materials are beginning to blur the lines between the solar, building, and power generation industries.

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About the Author

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