

Rapid Reactive Transfer Printing of CIGS Photovoltaics

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ABSTRACT

We demonstrate photovoltaic integrated circuits (PVIC) with high-quality large-grain Copper Indium Gallium Selenide (CIGS) obtained with the unique combination of low-cost ink-based or Physical Vapor Deposition (PVD) based nanoengineered precursor thin films and a reactive transfer printing method. Reactive transfer is a two-stage process relying on chemical reaction between two separate precursor films to form CIGS, one deposited on the substrate and the other on a printing plate in the first stage. In the second stage, these precursors are brought into intimate contact and rapidly reacted under pressure in the presence of an electrostatic field while heat is applied. The use of two independent thin films provides the benefits of independent composition and flexible deposition technique optimization, and eliminates pre-reaction prior to the synthesis of CIGS. High quality CIGS with large grains on the order of several microns, and of preferred crystallographic orientation, are formed in just several minutes based on compositional and structural analysis by XRF, SIMS, SEM and XRD. Cell efficiencies of 14% and module efficiencies of 12% have been achieved using this method. When atmospheric pressure deposition of inks is utilized for the precursor films, the approach additionally provides further reduced capital equipment cost, lower thermal budget, and higher throughput.

Keywords: Nanoengineered thin films, nanoscale self-assembly, thin film photovoltaics, Copper Indium Gallium Selenide, CIGS, photovoltaic integrated circuits, PVIC, reactive transfer printing

1. INTRODUCTION

Today's photovoltaic (PV) industry is dominated by panels made of crystalline silicon, which comprise the majority of the products on the market, typically installed in large ground-based energy farms and small roof-mounted systems. Despite tremendous (and growing) interest in harnessing the sun for energy, an imbalanced refined silicon feedstock supply coupled with inefficient manufacturing and installation processes continue to drive high costs that hamper the widespread adoption of solar electricity.

In recent years, a new generation of solar electric products has emerged from the lab into the global market. Much innovation centers around thin-film solar technologies that use approximately 1% of the active and expensive photovoltaic material to convert photons from the sun into electrons. Through a combination of cost advantages and new product applications, thin-film solar power generation is serving as a paradigm shift toward distributed electricity generation at cost parity with other forms of energy. CIGS has long been the most promising thin-film photovoltaic material, used for its high conversion efficiencies in advanced spacecraft applications, but has not had a reliable and rapid manufacturing process that could scale effectively and provide significant amounts of electricity at the point of use. The reactive transfer process is one such robust manufacturing process, enabling the rapid printing of microscale CIGS films with p-type and n-type nanodomains that are critical for achieving the highest efficiencies possible in this material system, while achieving high material uniformity on large substrates and high repeatability.

2. THIN-FILM PHOTOVOLTAICS

The most commonly used cost metric for PV is \$/W_p (often casually referred to as \$/W), measured in terms of manufacturing costs for the peak output of a given module. For example, the average industry cost for silicon PV is approximately \$3.50 for every watt of power a module could generate during peak hours. The goal that most thin-film PV companies are trying to reach is less than \$1/W_p; however, this metric is not adequate for representing customer concerns, namely getting the most power from a system over its lifetime. A module with rapid degradation in conversion efficiency over time or with inefficient energy conversion under low light conditions, could still have an attractive \$/W_p metric. Additionally, the balance of system cost (the additional components required for a complete, energy generating system) depends on the number of panels and means of installation. On

the other hand, the cents/kWh metric, that is the average cost of the energy (in cents) produced (in kilowatt-hours), takes into account all the power that will be produced by a module over its lifetime spread over the upfront capital costs of installation, thus representing the true value delivered by the module.

Thin-film photovoltaics encompass several different materials, each with their own unique properties. While all offer material advantages, they do differ in terms of conversion efficiency, lifetime expectancy, and manufacturing capabilities. Current market players beyond CIGS include amorphous silicon (a-Si) and Cadmium Telluride (CdTe). Additional early breakthroughs are being made with dye-sensitized solar cells (DSSC) containing titanium dioxide (TiO_2) nanoparticles coated with dye molecules, and organic photovoltaic (OPV) cells.

- a-Si: the most developed and well understood thin-film material, a-Si converts approximately 5-8% of solar irradiance into electricity and can be applied to both rigid and flexible substrates, with maximum laboratory efficiency levels achieved being at 13%.
- CdTe: with much recent success by manufacturing company First Solar, CdTe modules offer conversion efficiencies in the 6-10.5% range, with the maximum laboratory levels for small-area cells being at 16.5%. Due to the toxicity of input materials such as Cadmium, vendors reclaim and recycle modules, and the addressable market is constrained. Further, applications have been limited to rigid substrates.
- CIGS: the most efficient thin-film material, CIGS has achieved 20% efficiency in laboratory settings for small-area cells [1] and 13.5% for large-area modules [2], offering the possibility to compete on par with traditional crystalline silicon in the 12-18% product range. Applications include both rigid and flexible products.
- DSSC and OPV: the recipients of much recent R&D activity, these two technologies offer very low expected lifetimes (3-5 years) but very cost effective manufacturing options. Product applications are still in the exploration stage.

Table 1 summarizes the conversion efficiency values achieved in production modules and in record cells, for the three most mature thin film materials and for crystalline silicon.

| | Cell Material | Production Modules (2008) | Potential (Record Cell) |
|------------|---------------|---------------------------|-------------------------|
| Si Crystal | c-Si | 12-15% | 24% |
| | mc-Si | 10-13% | 20% |
| Thin Film | a-Si | 5-8% | 13% |
| | CdTe | 6-10.5% | 16.5% |
| | CIGS | 10-13.5% | 20% |

Table 1. Conversion efficiencies achieved in production modules and in record cells for leading thin film materials (a-Si, CdTe, CIGS) and for crystalline silicon (monocrystalline Si [c-Si] and multicrystalline Si [mc-Si]).

3. CIGS PHOTOVOLTAICS

CIGS thin-film photovoltaics offer a multitude of competitive advantages. First and foremost, CIGS has a high absorption coefficient, and it has a direct band gap that is well adapted to the terrestrial solar spectrum by being tunable, with gallium content, from about 1.0 to 1.7 eV. Most of the solar photons can be absorbed in the top 0.5 μm of an ideal CIGS film, or in about 1-2 μm of common CIGS films. The resulting relatively low material usage means that \$1 worth of silicon, the most expensive part of current photovoltaic modules, can be replaced with just \$.03 of CIGS materials. Furthermore, the silicon market has been constrained by an imbalance between supply and demand, resulting in manufacturers being tied to a volatile and unpredictable commodity market characterized by wide price fluctuations. CIGS production benefits not only from material advantages, but from potential for improving costs throughout the value chain, leveraging manufacturing maturity in related thin-film technologies such as the electronics and display industries.

In addition to manufacturing advantages, CIGS thin-film solar offers versatile aesthetic choices in product innovation. While the solar market has been unstable with frequent misalignment between supply and demand, differentiators such as appearance, a variety of rigid and flexible substrates, and the ability to adapt products to various market segments, will play an increasingly important role as the market approaches equilibrium. Some silicon PV companies have already proven that high-end products with a strong aesthetic advantage can attract significant investment and secure market share at a premium. CIGS thin-film builds on this idea, offering the highest conversion efficiencies of any thin-film material, with the additional opportunity of being integrated into a wide variety of building and construction materials, appealing to the aesthetics needed in different designs and applications. Semi-transmissive modules are also an option, which can serve the dual function of vision glass and electricity generation.

Among the thin-film photovoltaic materials, CIGS is the most promising for cost-effective power generation, offering the highest conversion efficiency and thus providing the maximum power per unit area available. This also means an attractive energy payback time: currently 1.5 years, with expected advances resulting in a payback time below 6 months in the next 5 years. Depending on the manufacturing technique, CIGS can also offer monolithically interconnected modules. This means that instead of discrete, individual cells that are packaged together, photovoltaic modules can take the form of photovoltaic integrated circuits (PVICs) to simplify the manufacturing process and further reduce costs (see Section 6). A similar approach has been taken and proven extremely effective for high throughput and manufacturing scalability of CdTe thin-film modules. While not all CIGS manufacturing processes can utilize PVICs, the reactive transfer process capitalizes on the advantages of this approach while also offering rapid deposition over large areas.

Furthermore, as shown in Table 2, CIGS modules have a higher average annual harvest (in kWh/m²) per rated absolute efficiency percentage point, making a 12% CIGS module equivalent to a 14% multicrystalline silicon module, increasing a customer's internal rate of return (IRR).

| Device Technology | Module Rated Efficiency | Average Annual Harvest (kWh/m ²) |
|------------------------|-------------------------|----------------------------------------------|
| mc-Si | 14% | 229 |
| a-Si (single junction) | 7% | 126 |
| CIGS | 12% | 223 |

Table 2. Rated module conversion efficiencies and average annual harvest achieved in multicrystalline Si, amorphous Si, and CIGS. (source: UT Austin EE Department)

Consistent testing on photovoltaic arrays at HelioVolt confirms 25% increased yield or harvest (in kWh/Wp) in CIGS modules over multicrystalline silicon module (Figure 1).

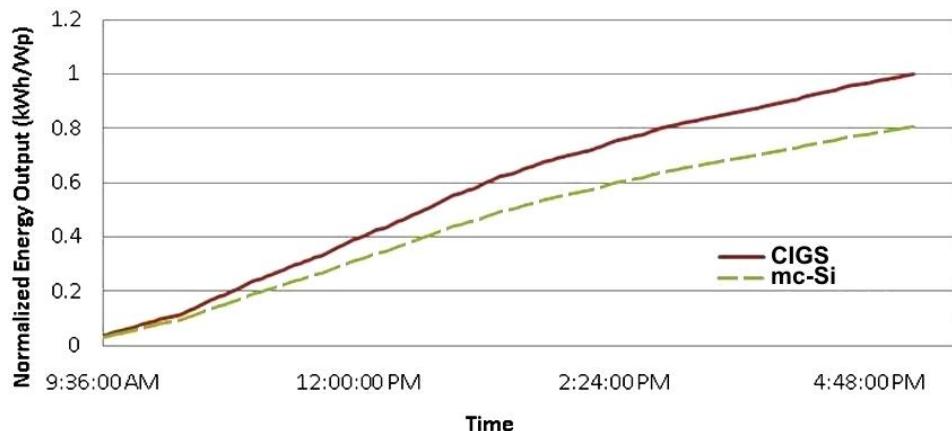


Figure 1. Energy output of CIGS and mc-Si PV arrays normalized to Wp installed.

4. HIGH PERFORMANCE CIGS MATERIALS

High-performance CIGS is characterized by (1) relatively large grain sizes, (2) an overall copper deficiency compared to the structure of the conventional α -phase Copper Indium di-Selenide (CuInSe_2), and (3) a composition lying in the equilibrium $\alpha+\beta$ 2-phase domain [3]. This latter characteristic is behind the Intra Absorber Junction (IAJ) model [4] that describes the formation within individual grains of α domains that Cu-rich with p-type conductivity and β domains that are Cu-poor with n-type conductivity, forming nanoscale p-n junction networks. The n-type networks act as preferential electron pathways, while the p-type networks act as preferential hole pathways, allowing positive and negative charges to travel to the contacts in physically separated paths, reducing recombination and improving efficiency.

Furthermore, gradients in a CIGS thin film are critical for the formation of a high-efficiency absorber. The gradients are the result of variations of relative fluxes and variations in the substrate temperature during material deposition, as well as a variety of diffusion and transport phenomena occurring at various stages of the deposition and the reaction processes.

Diffusion and transport phenomena that occur during the fabrication of CIGS thin films, and that require precise control, include:

- Equilibrium between Se atoms in CIGS, liquid Se, and Se vapor
- Relative diffusion of Ga and In
- Diffusion of the highly mobile Cu ions during the CIGS formation reaction
- Interdiffusion between the multinary compounds deposited, typically In-Ga-Se and Cu-Se layers
- Other diffusion creating composition gradient along CIGS film thickness
- Diffusion of Se into the Mo back contact – some MoSe_2 helps contact resistance, excessive MoSe_2 affects adhesion and Mo-CIGS electrical contact
- Diffusion of buffer elements (e.g., Cd, Zn, In) into the absorber
- Transport of Na from the soda lime glass (SLG) through the back contact into the absorber layer

Achieving steady improvement in CIGS efficiency until the maximum potential efficiency is reached, while achieving high uniformity, repeatability, and scalability, requires a fundamental understanding of diffusion phenomena and nanoscale self-assembly, which requires:

- Modeling the effect of process parameters on reaction pathways
- Modeling the effect of reaction pathways on kinetics and thermodynamics
- Modeling the effect of kinetics and thermodynamics on diffusion
- Modeling the effect of diffusion on material phases, composition gradients, and band gap gradings

HelioVolt process design and modeling scientists and process engineers, working with researchers at US government laboratories and universities, are building models based on continuous feedback between theory and experiment, and are applying the learnings to design and continuously improve the robust processes being used in HelioVolt's manufacturing lines.

5. CIGS BY REACTIVE TRANSFER

The conventional method used to synthesize high performance thin film CIGS devices is a high-temperature co-evaporation method. The multi-step deposition sequences developed to achieve this performance always involve the topotactic transformation of a fairly large grain precursor into very large grain CIGS rather than the direct synthesis of CIGS from condensation of elemental vapors as in molecular beam deposition. This same topotactic transformation is used by the reactive transfer process.

The reactive transfer process utilizes a two-stage reactive transfer printing method relying on chemical reaction between two separate precursor films to form CIGS. A schematic of the reactive transfer process is shown in Figure 2. In the first stage, two Cu-In-Ga-Se-based precursor layers, forming the chemical basis of CIGS, are deposited onto a substrate and a print plate, respectively. The two separate precursors provide the benefit of independently optimized composition, structure, deposition method, and processing conditions for each precursor. Separating the precursors eliminates pre-reaction prior to the second stage reactive transfer process, and facilitates optimized CIGS formation in the second stage. Furthermore, precursors can be deposited at a low substrate temperature enabling lower cost, and higher throughput.

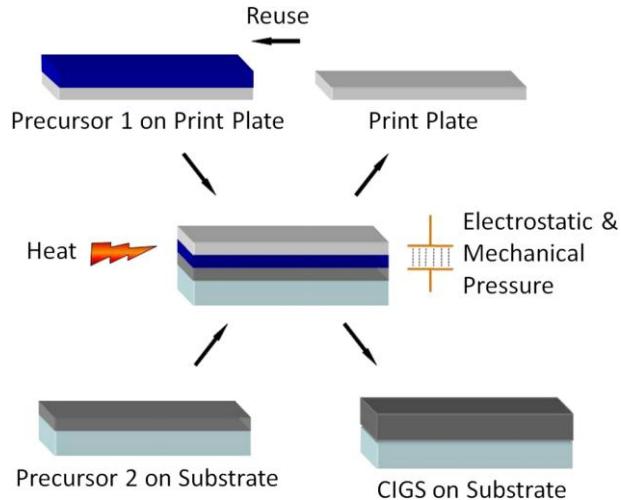


Figure 2. Schematic of the reactive transfer process.

In the second stage, these precursors are brought into contact and rapidly reacted under pressure in the presence of an applied electrostatic field. The method utilizes physical mechanisms characteristic of rapid thermal processing (RTP) and anodic wafer bonding (AWB), effectively creating a sealed micro-reactor that insures high material utilization, direct control of reaction pressure, and low thermal budget. The rapid thermal transient provides the similarity between the reactive transfer process and RTP. By pulse heating the film through the print plate, the overall thermal budget is significantly reduced, allowing the use of low cost less thermally stable substrate materials.

Sufficient mechanical pressure can substantially prevent the loss of Se vapor from the reaction zone, thereby achieving highly efficient incorporation of Se into the composition layer. The use of an electrical bias between the print plate and substrate creates between them an attractive force that serves to insure intimate contact between the precursor films on an atomic scale, and can thus be used in conjunction with mechanical pressure to control the total pressure in the reaction zone. This is the resemblance between the reactive transfer process and AWB, a method developed historically to reduce the temperature required to bond two dissimilar materials together.

5.1 Nanostructured CIGS Thin Films

Large grain high quality CIGS is synthesized from two precursors in five minutes using the reactive transfer process. Figure 3 shows a precursor film with its grains having dimensions on the order of a quarter micrometer, and the cross section of a reactive transfer printed CIGS film with its grains being columnar and having dimensions on the order of a micrometer.

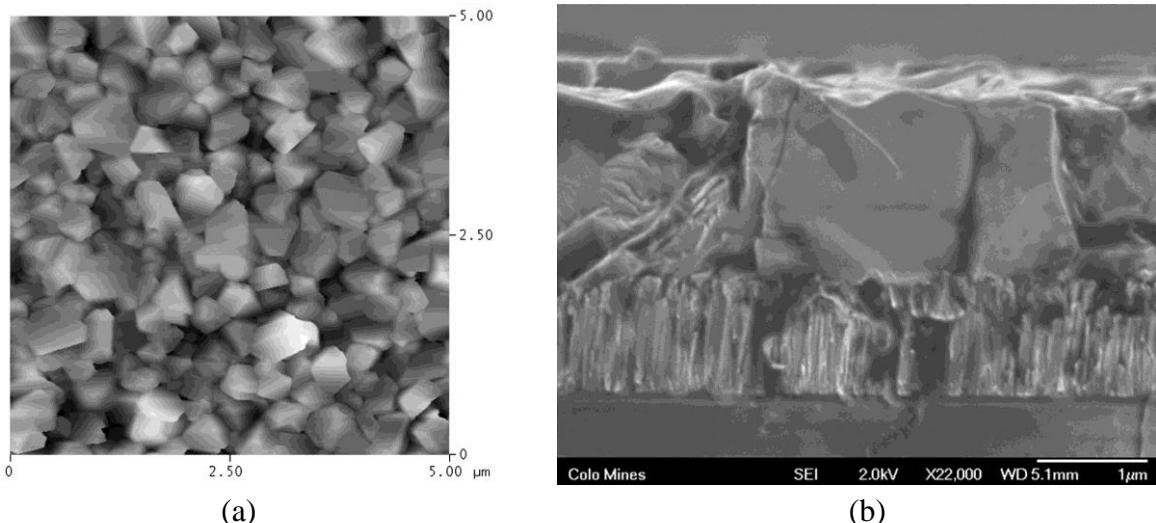


Figure 3. (a) Precursor film and (b) reactive transfer CIGS cross section.

Figure 4 shows a secondary ion mass spectrometry (SIMS) depth profile of a CIGS thin film processed by reactive transfer. The precursors for the film are made by physical vapor deposition (PVD) methods. The uniform elemental distribution indicates a complete reaction of the precursors, and the X-ray diffraction (XRD) analysis (Figure 5) confirms the absence of deleterious phases other than CIGS. All the XRD peaks are indexed based on chalcopyrite-type CIGS and Mo structure. The reactive transfer processed film has a (220/204) preferred orientation. Evidence indicated that the (220/204) oriented films help junction formation and improve solar cells performance [5]. The rapid processing of CIGS formation significantly increases the manufacturing throughput. As described above, this unique processing approach results in a much lower thermal budget as compared to co-evaporation and two-step selenization processes, which are common CIGS manufacturing. The lower thermal budget, removal of selenization process and high throughput all contribute to a low cost process leading to improved manufacturability.

The opportunity to tailor the two precursors independently allows for the use of unconventional, non-vacuum deposition techniques such as die extrusion coating, ultrasonic atomization spraying, pneumatic atomization spraying, inkjet printing, direct writing, and screen printing. These atmospheric-pressure-based deposition tools offer great flexibility and open up entirely new windows for materials processing. They also offer a viable means of introducing nanoparticle technology, metal organic chemistry and novel reaction paths to produce CIGS. The low capital equipment cost and high throughput capabilities associated with atmospheric pressure processing potentially reduce manufacturing cost. These materials can be deposited in air at temperatures below 200°C, which will lower the thermal budget [6].

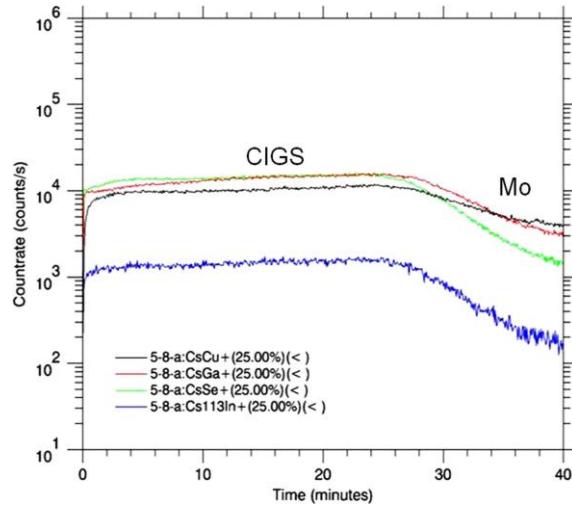


Figure 4. SIMS depth profile of a CIGS film. This film was formed in six minutes by the reactive transfer process.

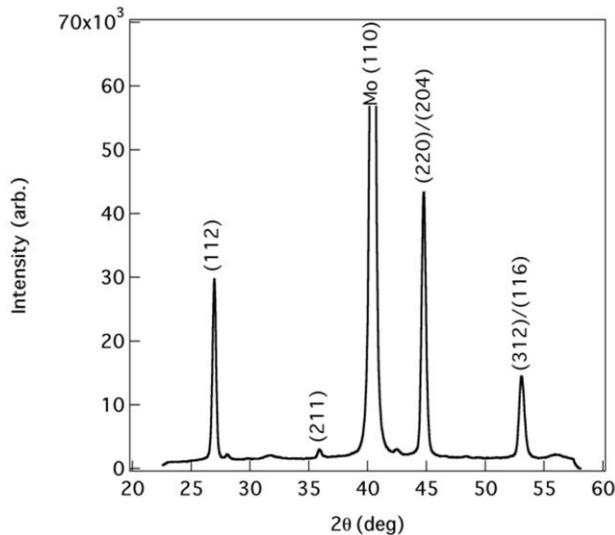


Figure 5. XRD pattern of a CIGS film fabricated by the reactive transfer process.

Proprietary inks containing a variety of soluble Cu-, In- and Ga- multinary selenide materials have been developed. These metal-organic inks are designed to decompose into the desired precursors, and are called metal-organic decomposition (MOD) precursors. The resultant precursors are then used in step one of the reactive transfer process. For the work described in this chapter, the inks were deposited using an ultrasonic spray head fed by a variable speed liquid pump. A substrate heater mounted on a computer-controlled X-Y motion system allowed for movement of heated substrates under the sprayed stream. The thickness of the sprayed film was controlled by varying the ink concentration, the flow rate through the sprayer and the number of coats sprayed. Conditions were optimized such that smooth, uniform precursor films were obtained for all of the sprayed inks.

The precursor films were converted to the desired materials through rapid thermal processing (RTP) in a controlled atmosphere. The RTP conditions were varied systematically to ascertain the effect of conditions on the film compositions and morphologies obtained. The film compositions were characterized by X-ray fluorescence (XRF), crystalline phases were identified using XRD and film morphology was examined using scanning electron microscopy (SEM).

Binary Cu-Se, In-Se, and Ga-Se materials were developed and used to produce precursors. Various formulations of Cu-Se MOD precursors were also produced, resulting in tunable phase and stoichiometry in as-deposited films. Figure 6 shows the crystalline phase of Cu-Se films that can be produced from a single MOD ink, ranging from phase pure CuSe₂ to Cu₂Se.

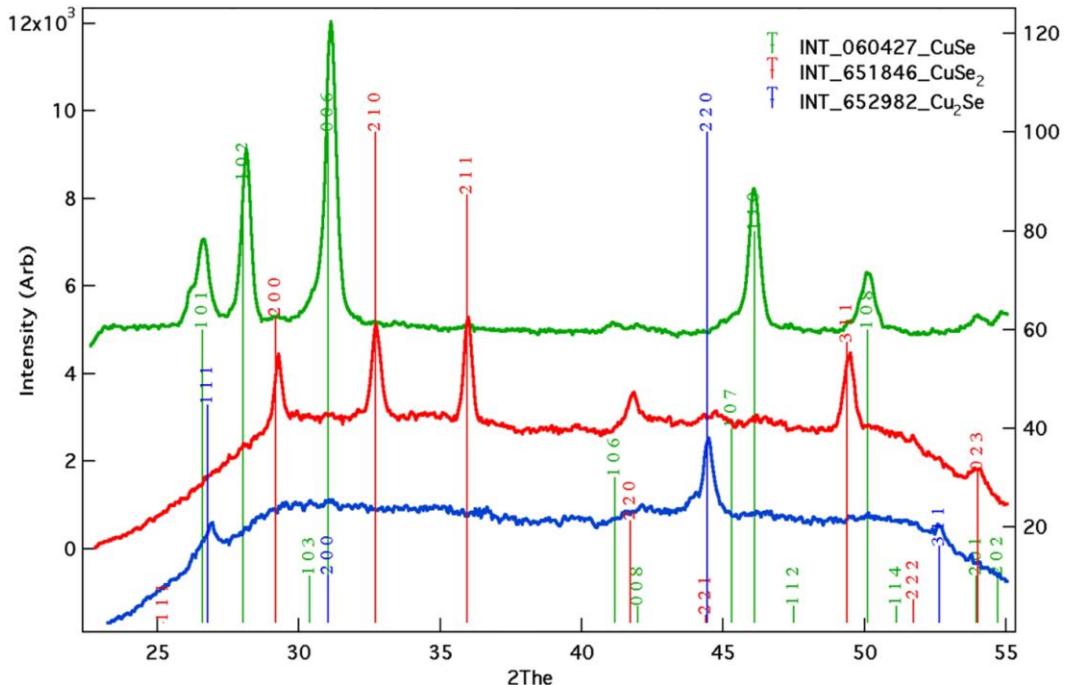


Figure 6. Range of crystalline Cu-Se phases obtained from a single MOD ink.

Figure 7 compares the cross-sectional morphology of vapor deposited CuSe films to that of atmospheric MOD CuSe films. The remarkable similarity between grain size, morphology, and density shows the promise of using solution-based precursors as substitutions for vacuum deposition processes. All temperatures used were below 200°C. This result represents a breakthrough for solution-based precursors.

Hybrid CIGS is produced by reactive transfer when one of the precursors is PVD-deposited in vacuum and the other precursor is atmospheric-pressure-deposited from an ink. Figure 8 shows cross-sectional and top view SEM micrographs of such a hybrid CIGS film, revealing high quality large columnar grains up to 4 μm in size.

The XRD pattern for the Figure 8 sample is shown in Figure 9 and the chalcopyrite CIGS phase is clearly identified. Again, (220/204) textured film is made by the reactive transfer process. These CIGS films are being applied to solar devices.

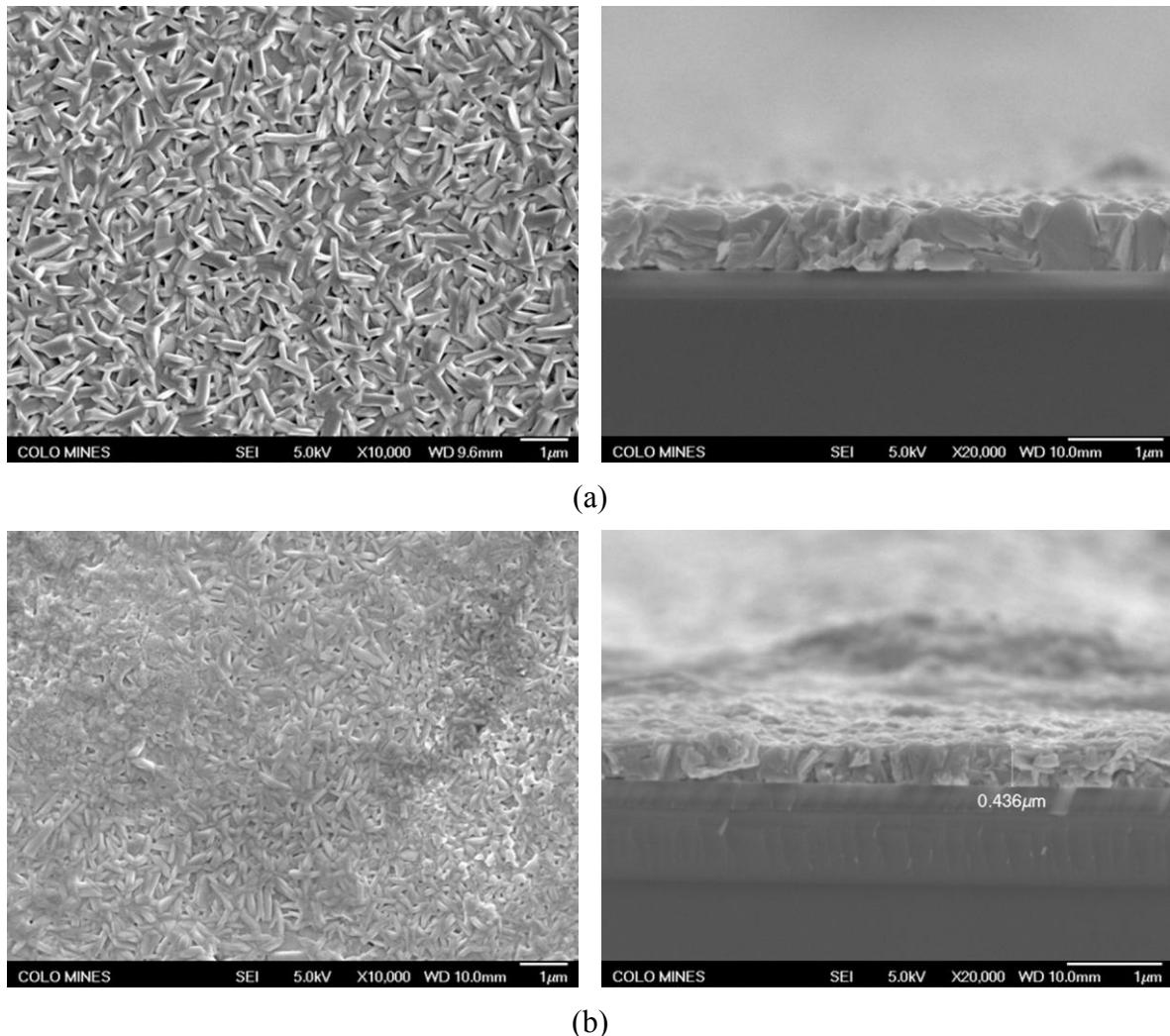


Figure 7. Top views and cross-sectional SEM views of (a) a PVD deposited CuSe film, and (b) an atmospherically spray-deposited CuSe film from a solution-based process.

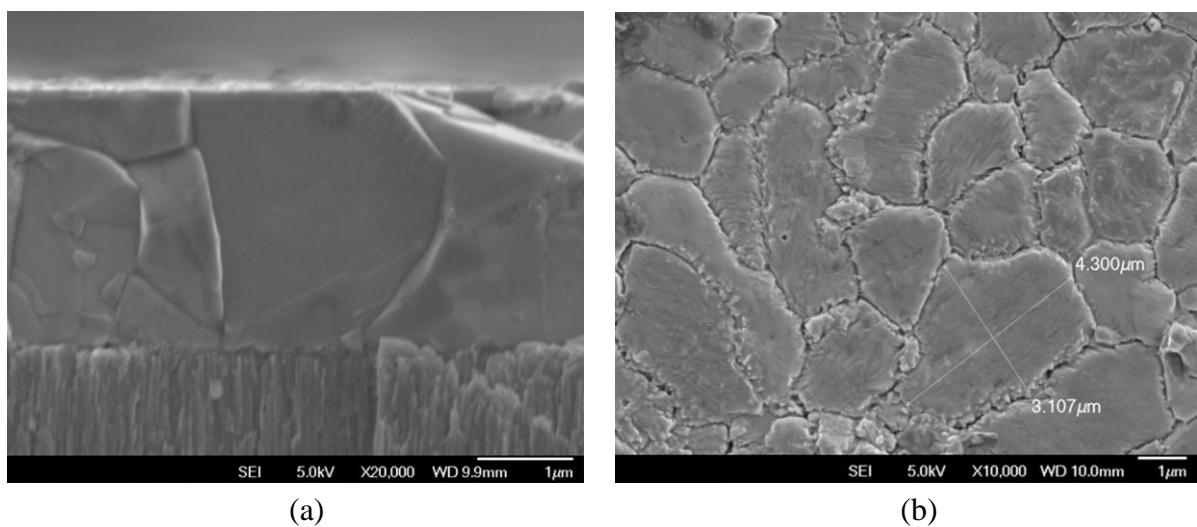


Figure 8. SEM micrographs of (a) the cross section and (b) the top view of a CIGS film synthesized using a non-vacuum-deposited precursor.

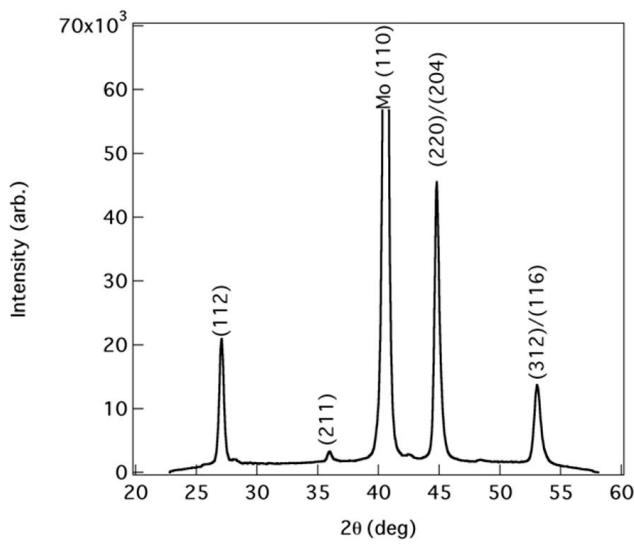


Figure 9. XRD pattern of a CIGS film by reactive transfer using a non-vacuum deposited precursor.

An important benefit of the reactive transfer process is that there is no constraint on the combination or type of precursors that can be brought together. The only requirement is that all of the elements in the correct stoichiometry must be present on the substrate and print plate prior to the reactive transfer process.

The tunability, scalability, high throughput, low thermal budget, and capital equipment cost reduction that atmospheric processing of MOD precursors provides is a promising route to potentially replace vacuum deposition methods for CIGS absorber layer fabrication.

From a manufacturing standpoint, any deposition method, whether it is PVD-based or atmospheric-pressure-based, has relative advantages and disadvantages. While the capital equipment cost for atmospheric-pressure-based systems is lower than that of the corresponding PVD systems, the raw material costs tend to be higher for solution rather than for PVD sources. Therefore, the best choice is ultimately governed by differences in the performance and yield of products manufactured by these two approaches. Better material utilization coupled with the decreasing cost of liquid precursors due to the maturation of the nanotechnology field make atmospheric-pressure-based processing a more attractive alternative.

5.2 Solar Cells Based on Nanostructured CIGS Thin Films

Solar cells with a conventional device structure of glass/Mo/CIGS/buffer/TCO were fabricated. The CIGS absorber in these cells was formed by the reactive transfer process with PVD-based precursors. Figure 10 shows a cross-sectional schematic of a typical CIGS solar cell. The SEM micrograph in Figure 12 depicts a cross section of a representative device. As can be seen, high-quality CIGS films with large columnar grains are obtained.

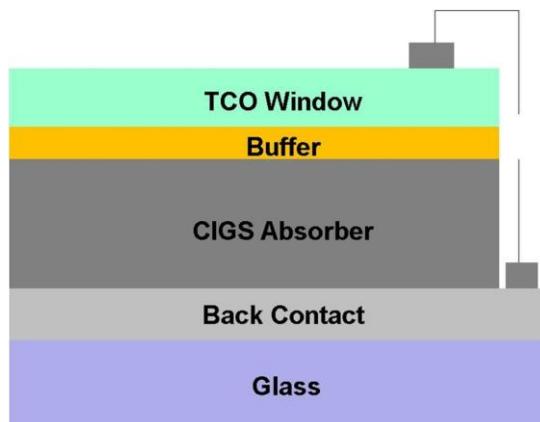


Figure 10. Cross-sectional schematic of the material stack in a typical CIGS solar cell.

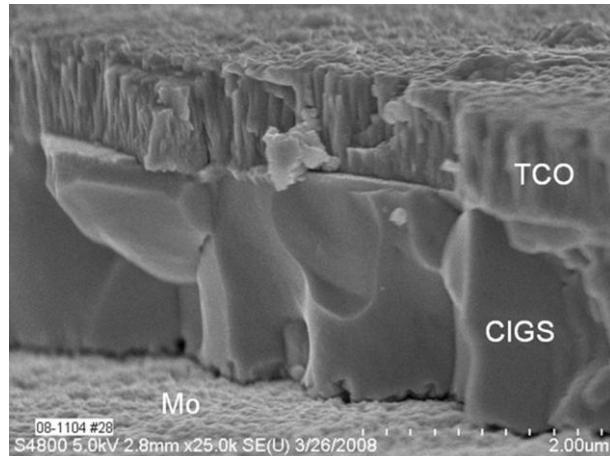


Figure 11. SEM cross-sectional image of a reactive transfer CIGS device.

External quantum efficiency (QE) versus wavelength for the device without anti-reflection (AR) coating is shown in Figure 12. High QE at wavelengths over 550 nm reveals very good carrier collection and good performance of the CIGS layer. A relatively low QE at short wavelengths indicates the need to further optimize window layers.

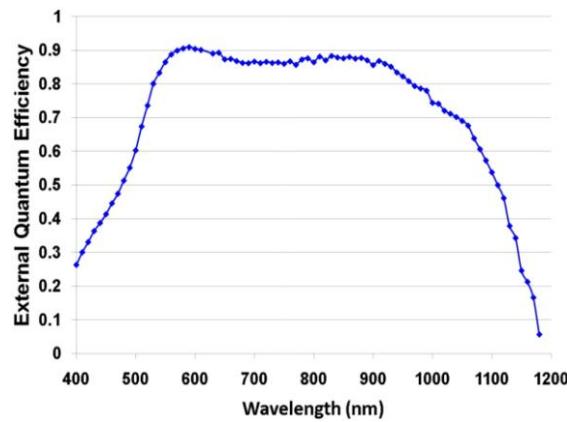


Figure 12. QE curve of a reactive transfer CIGS solar cell.

Solar cells of over 14% efficiency have been fabricated using the reactive transfer process. A J-V curve of a 14.0% efficient device is shown in Figure 13. The V_{oc} is 630.5 mV, the J_{sc} is 30.9 mA/cm², and the FF is 71.8%.

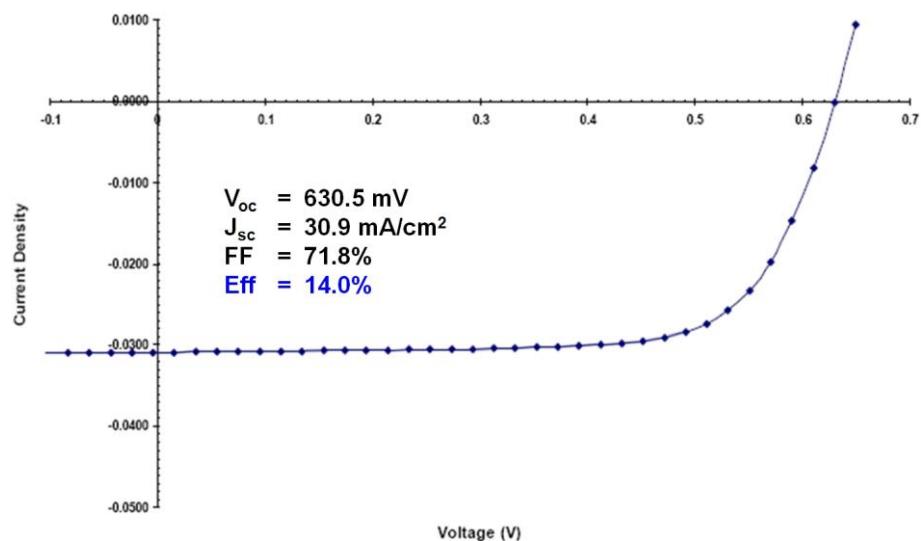


Figure 13. J-V curve of a 14%-efficiency HelioVolt CIGS solar cell.

6. CIGS MONOLITHICALLY INTEGRATED MODULES

A monolithically integrated CIGS module consists of a packaged photovoltaic integrated circuit (PVIC). In a PVIC, the thin films are deposited on a substrate and undergo a series of scribe patterning steps that create a monolithically interconnected integrated circuit of cells in series. The integrated approach circumvents the significant cost associated with cell cutting, testing, sorting, tabbing, and stringing, processes that are labor-intensive. Some thin-film PV technologies that do not take advantage of this essential cost advantage that thin film PV modules can have over crystalline silicon based modules.

The reactive transfer process prints CIGS directly on a variety of rigid and flexible substrates, including:

- Glass
- Metals
- Alloys
- Composites
- Plastics

Soda lime glass (SLG) produced by the float process is the most commonly used substrate material, and has produced some of the best results in terms of both performance and reproducibility. It meets cost, smoothness, and stability criteria, making it well suited for commercial production. One limitation that needs to be addressed in the development of production processes is that soda lime glass starts to soften above 520°C, as it goes through its glass transition temperature (Tg) range of 520-600°C. Sodium, an important element to have in the CIGS film for the formation of high quality large grain crystals, can be transported controllably from the SLG into the CIGS thin film through the back contact, or can be added in controlled amounts.

Flexible substrate materials can be attractive either for manufacturing lightweight flexible products for some applications or for the use of low-cost roll-to-roll deposition processes in manufacturing. Flexible substrate materials on which good performance was achieved include polyimide, titanium, and stainless steel [7, 8]. The main drawback of polyimide is low temperature tolerance, since the best commercially available polyimide films can withstand temperatures only up to 450°C; another drawback is high thermal expansion. The main drawback of titanium and steel is their conductivity, requiring an electrically isolating layer in order to allow monolithic integration; the isolation layer needs to be void of defects that cause shunting of the cells. For these flexible substrates, sodium needs to be introduced.

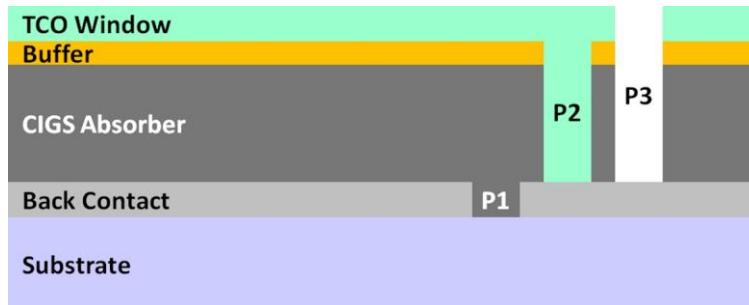


Figure 14. Cross-sectional schematic of the material stack in a typical CIGS PVIC, showing the three scribe patterns (P1, P2, P3) that achieve the isolation and interconnection between two segments.

A typical monolithic interconnection scheme involves three main patterns, as illustrated schematically in Figure 14. The first pattern (P1) consists of isolation lines cut in the back contact (usually Molybdenum) typically using laser ablation, prior to the CIGS deposition. Mechanical scribing is typically used for the two subsequent patterning steps (P2 and P3), where the P2 lines are cut through the buffer and the CIGS down to the back contact, then filled with TCO as the interconnect material, and P3 lines are cut through the TCO, buffer, and CIGS down to the back contact to complete the isolation of the cell. The scribe zones between active segments create a pin-stripe pattern, as can be seen in Figure 16. The interconnect pattern can be designed to fit various shape and voltage requirements. An additional patterning step known as edge deletion is performed on the module level (as opposed to the segment level), where the thin film materials are removed from the outer rim of the substrate in order to improve the adhesion to the encapsulant used during lamination. This step completes the fabrication of the PVIC.

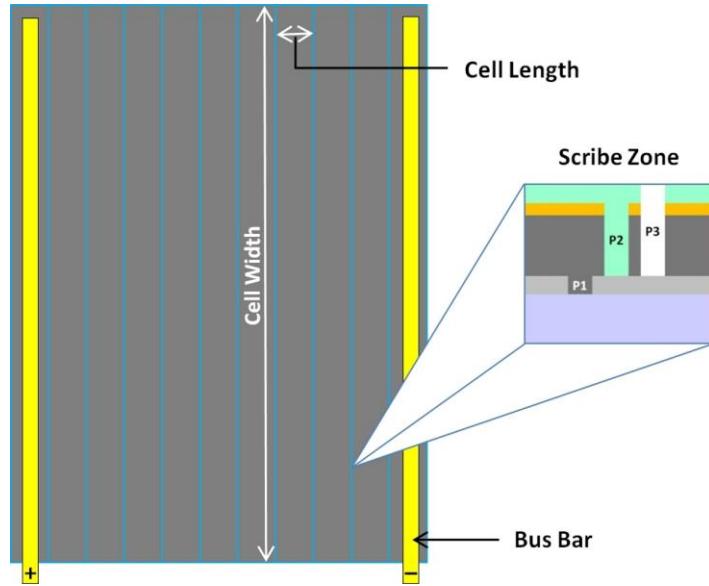


Figure 15. Schematic of a CIGS PVIC with bus bars. The scribe zones between active segments create a pin-stripe pattern.

The PVIC goes through packaging in order to become a module. Bus bars are attached to avoid resistive losses associated with current collection; these metal stripes can be soldered, welded, or glued to contact areas near the substrate edges, as shown in Figure 15. A superstrate is laminated to the substrate using an encapsulant sheet made of a material that is optically transparent and can withstand environmental and UV exposure. The encapsulant, commonly ethylene vinyl acetate (EVA), also serves the purpose of protecting the PVIC from moisture. An edge sealant can additionally be used for further protection from the environment. A junction box is typically integrated with connectors for creating module strings. The junction box must capture and seal the bus bar exit zone, and it often integrates a bypass diode to protect the module string from partial shading losses. Framing finishes the module, but can be omitted for some applications such as solar farms.

HelioVolt started scaling up its PV technology from the cell level to module level by first creating a G1 platform for modules. The G1 form factor is 30 cm x 30 cm. With the 14% efficiency level achieved in HelioVolt cells (Figure 13), the predicted equivalent efficiency for modules is 12%, if the material quality achieved in a cell is achieved uniformly across the area of the module, with the power loss from 14% to 12% resulting mainly from the non-active ‘dead’ areas with the scribe lines and from the greater requirements on lateral conduction in the TCO. Modules with 12% efficiency were produced, and one such module showing the uniform CIGS film is shown in Figure 16.

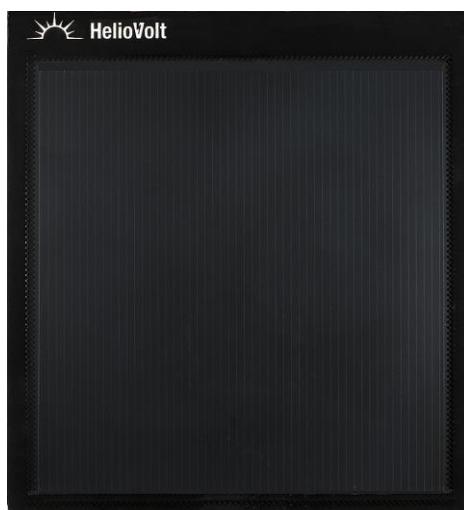


Figure 16. Photograph of a G1 HelioVolt module measuring 30 x 30 cm².

A module measured by HelioVolt at 12.03% efficiency (Figure 17(a)) was independently verified by the National Renewable Energy Laboratory (NREL) where $11.6 \pm 0.6\%$ efficiency was confirmed, as shown in Figure 17(b).

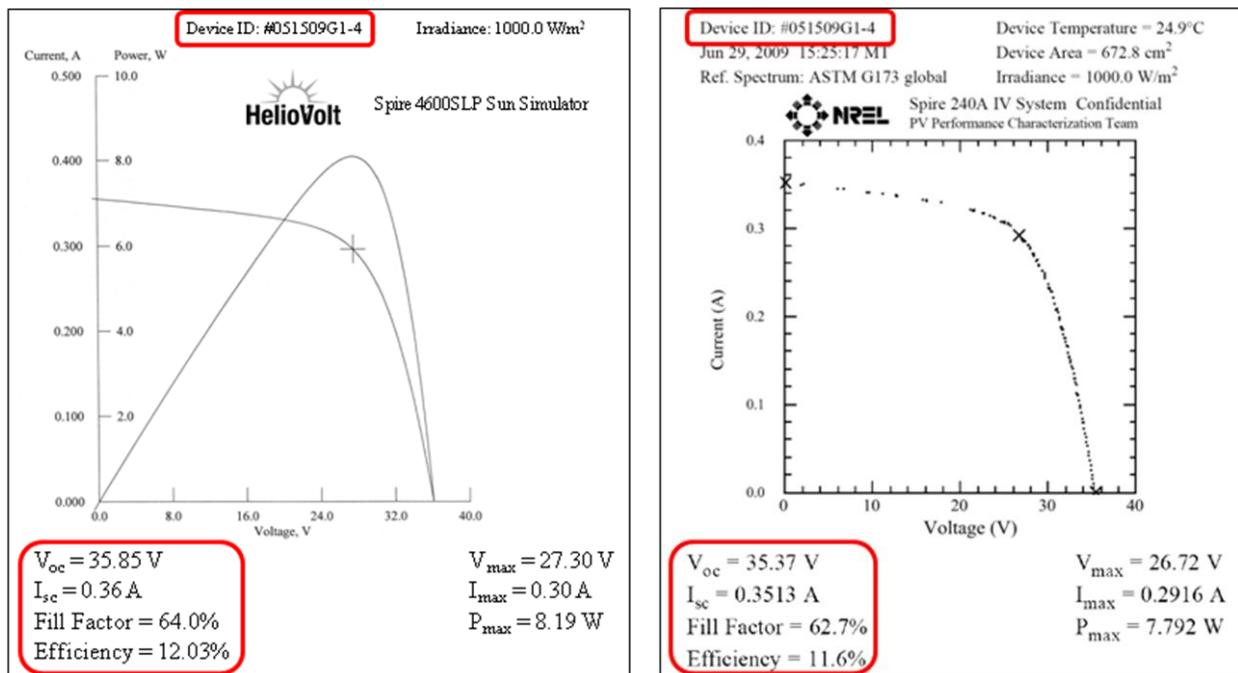


Figure 17. Light current-voltage (I-V) curves measured by HelioVolt and NREL on a HelioVolt G1 module with efficiency around 12%.

A 20 MW manufacturing line at HelioVolt's first factory in Austin, TX is producing G2 modules, with a form factor of 120 cm x 60 cm. Figure 19 shows a G2 module produced on this line.

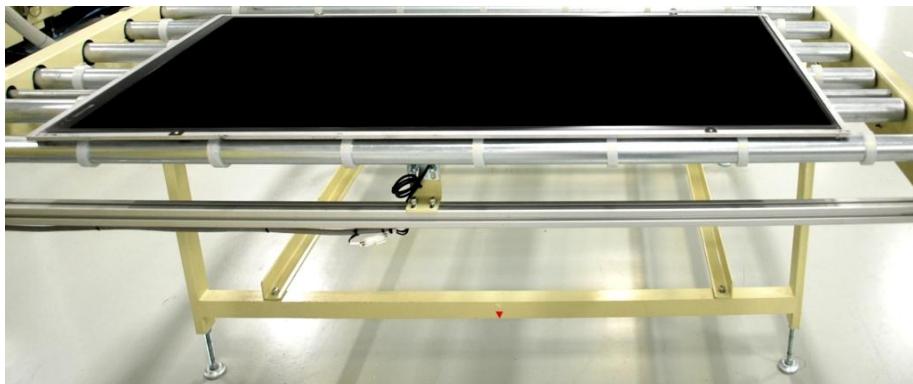


Figure 18. G2 module produced at HelioVolt's first manufacturing line in Austin, TX.

7. CIGS PHOTOVOLTAIC MODULE RELIABILITY TESTING AND CERTIFICATION

The reliability of PV modules over time is critically important, along with the initial cost and efficiency, if a PV technology is to make a significant impact in the power generation market, and for it to compete with conventional electricity producing technologies. The reliability of photovoltaic modules has progressed significantly in the last several years, as evidenced by warranties as long as 25 years available on commercial modules.

Accelerated reliability testing in laboratories includes testing under stressing conditions of:

- Temperature
- Voltage
- Current
- Moisture
- Thermal cycling
- UV-visible radiation
- Mechanical impact

Certification testing requirements per UL (Underwriters Laboratories) and IEC (International Electrotechnical Commission) are tabulated in Table 3. The main reliability and safety standards for PV panels are UL-1703, IEC-61646 and IEC-61730.

| Test | Description |
|-----------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Performance | <ul style="list-style-type: none"> • +/- 10% of specified electrical parameters |
| Outdoor Exposure | <ul style="list-style-type: none"> • 60 kWh/m², maintain performance |
| Thermal Cycling | <ul style="list-style-type: none"> • -40 to +90°C |
| Damp Heat | <ul style="list-style-type: none"> • 85°C / 85%RH |
| Humidity Freeze | <ul style="list-style-type: none"> • -40 to +90°C with condensation |
| Mechanical Robustness | <ul style="list-style-type: none"> • Shading hot spot • Connectors/J-box pull test • 400 lb weight loading • Steel ball impact (51", 1.18 lb) |
| Shock Hazard | <ul style="list-style-type: none"> • No leakage current after environmental exposure |

Table 3. Key PV panel certification tests per UL and IEC reliability and safety standards.

8. APPLICATIONS OF CIGS THIN FILM PHOTOVOLTAICS

The compatibility of the reactive transfer process with a variety of rigid and flexible substrates means that, depending on market needs and demands, a wide variety of products can be produced, from traditional glass modules to building construction materials that incorporate thin-film photovoltaics. By integrating PV into building construction and design, further system level advantages are available and costs can be reduced even more by leveraging the construction material installation. Moreover, new market applications are possible, as solar breaks from rooftop installations and ground-mounted energy farms into architectural design and building façades. Building-integrated PV (BIPV) is a paradigm shift for solar, enabling communities and buildings with a solar-powered “skin.” Distributed generation through BIPV means that the building is the power plant. This will open the door to a new large industry that is the intersection of the construction and power generation industries.

Aesthetically, the solid dark grey appearance of CIGS modules is usually preferred to the non-uniform bluish appearance of the crystalline silicon modules in BIPV applications. CIGS can offer the appearance of tinted glass on the sides of buildings, or that of slate on rooftop applications.

For space applications, CIGS panels offer other advantages since their radiation tolerance is higher than that of crystalline silicon panels [9, 10]. Furthermore, lightweight plastic substrates could lead to solar cells with very high specific power (power divided by mass), an important requirement in some space applications [11].

In the near future, CIGS can be incorporated into everyday lives in entirely new ways. Solar skins will become pervasive not only in roofing, curtain walls, and façades, but also in sunshades (Fig. 19), skylights, atriums, canopies, and pergolas. Further, BIPV will come in a variety of form factors, shapes, colors, and transparencies, and will incorporate dynamic behavior and innovations in lighting, heating, and cooling.



Figure 19. HelioVolt CIGS BIPV panels used as sunshades.

9. CONCLUSION

The reactive transfer process produces high performance CIGS devices rapidly and at low cost, based on harnessing the key elements required for the creation of the highest quality materials. Reactive transfer printing, especially combined with the use of liquid ink precursors, provides a sustainable long-term technology-based cost advantage and opens the doors to further advances in the manufacturing of CIGS thin-film photovoltaics.

The reactive transfer process is a two-stage reactive transfer printing method relying on chemical reaction between two separate precursor films to form CIGS. The very short processing time, low thermal budget, and high material utilization, lead to a low cost process. CIGS films with large grains on the order of several microns and preferred (220/204) crystallographic orientation textured were produced in under a minute using both PVD-based precursors and non-vacuum-deposited precursors. Devices achieved conversion efficiencies of 14%, and modules achieved 12% conversion efficiencies and were certified by NREL. HelioVolt's proprietary reactive transfer process was scaled up on a 20 MW production line.

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