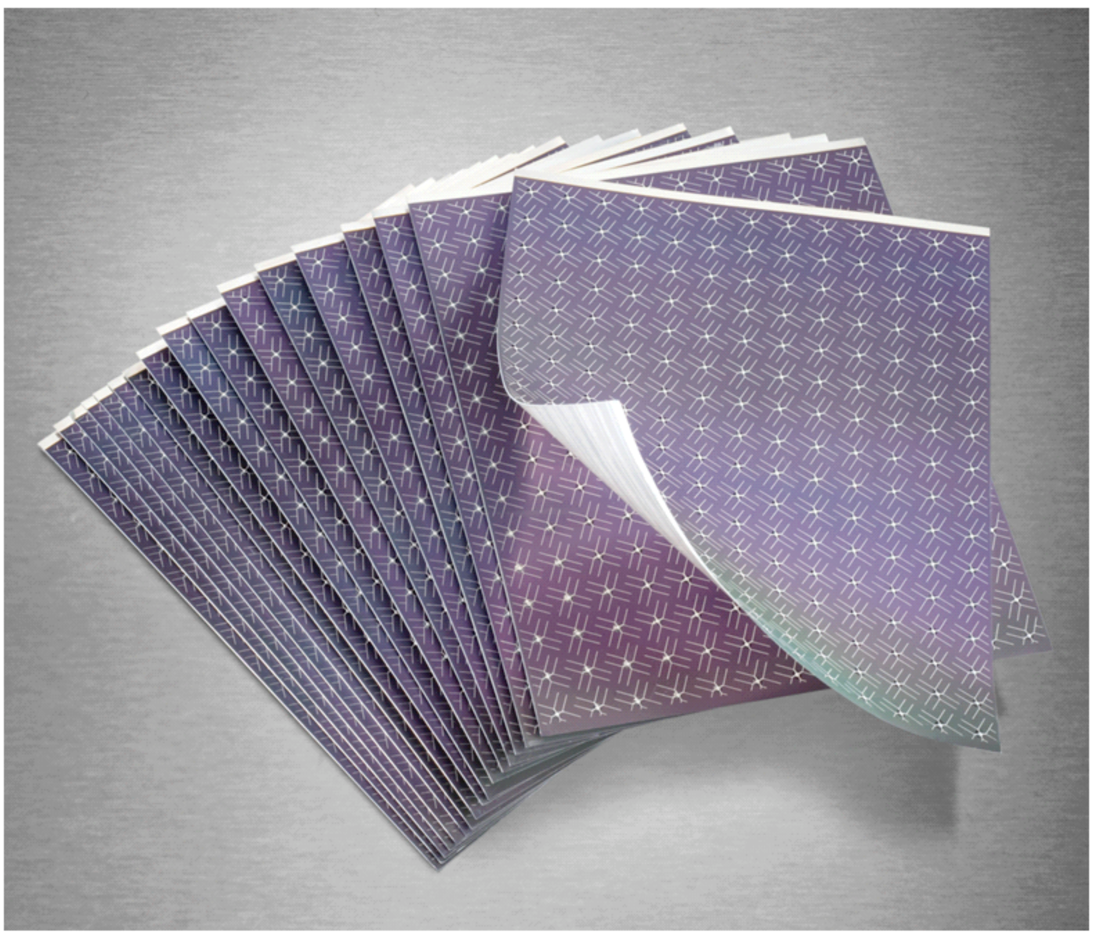
Ultra-Low-Cost Solar Electricity Cells

An Overview of Nanosolar's Cell Technology Platform

September 2009



Nanosolar Cells: CIGS Printed on Aluminum Foil Back-Contacted with Metal-Wrap-Through Design.

Ultra-Low-Cost Solar Electricity Cells

An Overview of Nanosolar's Cell Technology Platform

Through aggressive innovation deep in science and engineering, Nanosolar has developed a new generation of solar electricity cells with distinctly superior product cost and production capital efficiency. This White Paper describes the cell architecture and cell technology platform we have developed.

Introduction

Nanosolar was founded in 2002 to make solar power inexpensive through Silicon Valley style technology innovation. Since 2004, we have focused on executing a plan of reinventing CIGS – the most efficient and stable photovoltaic thin-film semiconductor – for superior cost and capital efficiency, targeting a cost/performance level not considered achievable by many experienced experts and institutions.

After five years of intense development and perseverance, we have delivered on our cost objectives, attained IEC 61646 & 61730 product certification, and are now in serial production, with our production run rate presently set at a sub-capacity level consistent with our market-introduction business objectives.

In order to realize the extent of this advance in cost efficiency, we addressed a host of fundamental science and engineering challenges. We developed a completely new semiconductor synthesis process with novel nanostructured materials, novel substrate and cell-architecture technologies, and new tooling designs to implement all of this as part of a new continuous-processing manufacturing framework.

With a development time of 15 years experienced by each successful industry precedent for a fundamentally new process technology, we took an approach of accelerating development by simultaneously conducting

- fast-cycle research conducted continuously on a foil-coupon basis in an industrially streamlined laboratory (which today sustains an experimental throughput of 10,000 experiment samples *per week*);
- five incremental generations of roll-to-roll processing tool designs built between 2005 and 2008; and
- production lines built and exercised at incrementally higher throughput, both in the form of a wider web (going from a 100mm line to a 200mm line, to a 750mm line, and as wide as 1500mm) and faster web speeds (going from 0.3m/min to as fast as 30m/min during certain process steps).

Technology Overview

CIGS is a photovoltaic semiconductor device technology well-known for its high energy conversion and durability potential, but also for its high-cost, challenging manufacturing using conventional (high-vacuum) techniques. At Nanosolar, we have taken this basic semiconductor device technology and completely reinvented it for distinctly superior cost and capital efficiency, attacking these factors for every process step in order to achieve the desired improvement.

Our team has developed an ultra-low-cost solar cell based on five principal bodies of technological innovation:

(1) the use of a highly conductive, low-cost aluminum foil as the substrate and bottom electrode of the cell;

(2) a CIGS ink with loaded-in stochiometric ratio and a high-yield high-throughput printing process to form an electronic-grade CIGS semiconductor;

(3) a novel Metal-Wrap-Through (MWT) back-contact design based on high-throughput foil lamination;

(4) a thin/printed transparent top electrode; and

(5) redesign and development of materials deposition processes that work with and leverage the superior steady-state uniformity and other characteristics inherent in roll-to-roll processing.

These five bodies of innovation address each component of a solar cell and its cost and capital efficiency, delivering the definitive improvement necessary to obtain an ultra-low-cost product: Innovation (1) delivers low materials cost, a low-cost substrate, and a low-cost bottom electrode (which otherwise would have to be created through an expensive thin film). Innovations (2+5) deliver a low-cost absorber/semiconductor with high material utilization and supreme capital efficiency. Innovation (3+4) enables a low-cost top electrode and simple, fast, robust cell interconnects.

The combination of a highly conductive aluminum substrate with our MWT cell architecture results in cells capable of generating and carrying currents of 6-25 Amps, or 3-10x more than is cost efficient with state-of-the-art thin-film solar cells today. Panels built with such high-current cells result in significantly lower balance-of-system cost when deploying large-scale systems (see the Nanosolar Utility Panel White Paper).

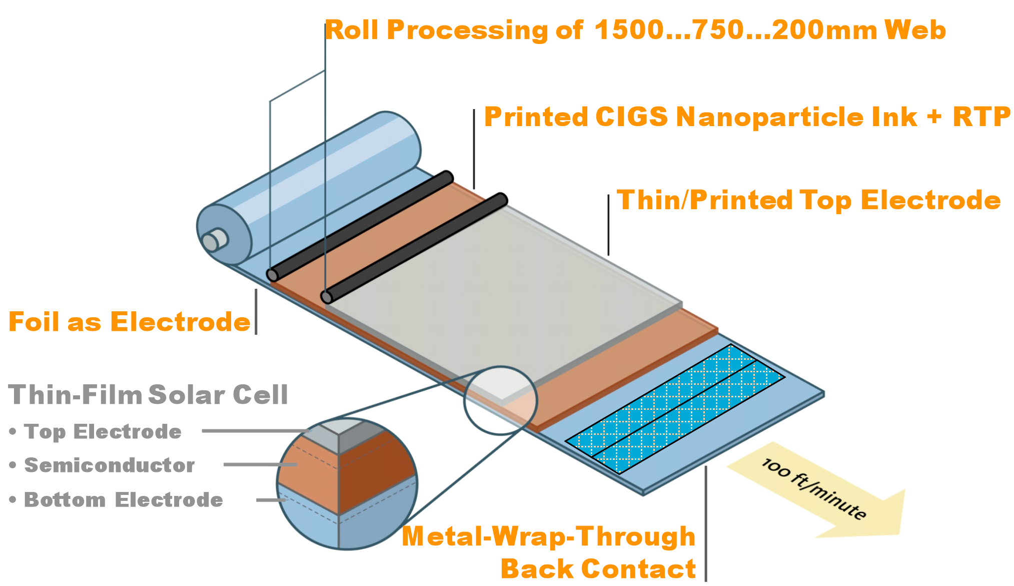


Figure 1: Nanosolar combines a host of innovations to deliver a distinct overall cost reduction.

Thin-Film-on-Foil versus Thin-Film-on-Glass

A key first-order technology choice is whether to deposit the stack of solar-cell thin films that make up the device onto a piece of glass ("thin-film-on-glass") or onto a foil ("thin-film-on-foil"). Using glass as a substrate is technologically more straight-forward and has been used in the first generation of manufacturing implementations in the industry. Foil as a substrate has been less developed. Key implications of this choice are the following:

- Using flexible foil is necessary if one wants to be able to apply the economics of roll-to-roll processing to the production of solar cells (with all its benefits and challenges) – whether or not one chooses a panel form factor package that is flexible. The most conservative and bankable product package is presently a glass/glass laminate package into which foil cells are embedded.
- For CIGS, which is a "substrate" stack (that is, the non-transparent bottom electrode is deposited first; as opposed to CdTe, which is generally a "superstrate" stack, with the transparent top electrode deposited first), one cannot produce a (lighter-weight) glass/foil-packaged panel product if one uses the thin-film-on-glass approach. A glass/foil product package weighs significantly less and is also somewhat less expensive than its glass/glass counterpart.
- A panel package for thin-film-on-foil cells can use tempered glass in both the front and back of a glass/glass package and thus create a product package of superior mechanical strength. Using tempered glass as part of a thin-film-on-glass package would be ineffective, as it would detemper during the high-temperature steps of the thin-film-on-glass processing. Tempered glass is substantially stronger than untempered glass (by a factor of approximately three) and a very economic choice for achieving mechanical strength.
- Thin-film-on-glass necessitates monolithic cell integration which, albeit elegant, carries a high penalty in terms of yield management and manufacturing ramp speed possible (see below).
- Thin-film-on-foil enables testing of individual cells and allows a decoupling of cell design issues from market/customer relevant panel design issues. Furthermore, thin-film-on-foil enables a flexible and versatile range of product packages, responsive to shifting market requirements, without the need to update or replace cell production equipment. With cell production equipment requiring substantial amounts of capital investment one way or another, tooling obsolescence risk should not be an underestimated issue.
- Glass has a high thermal budget, making truly rapid thermal processing (RTP) for the formation of the semiconductor not viable in the same way as on a highly thermally responsive substrate such as aluminum foil. (Nanosolar is particularly exploiting this advantage for truly rapid processing.)

However, given that there is approximate cost parity between a glass and a foil back encapsulant, the carrier foil used in a thin-film-on-foil approach has to be recognized as cost overhead that needs to be minimized and/or made up with other advantages of using foil. In addition to the cost of the foil, there is also the added cost of the adhesive between the foil and the back glass that needs to be made up. This means that thin-film-on-foil can be superior but only when a marginal-cost foil is used that delivers cost and/or capital savings on other aspects of the total cell and panel package. At Nanosolar, we believe the only path to success with thin-film-on-foil is in mastering the use of aluminum as a foil substrate (as unconventional and inconvenient a choice this might be for a solar-cell technologist) and realizing massive capital expenditure savings associated with using it as a bottom electrode.

CIGS-on-Conductive-Foil Using Aluminum

Nanosolar uses an approach to thin-film-on-foil that employs a foil that is highly conductive: aluminum.

Aluminum foil is one of the least expensive materials – effectively as inexpensive as the cheapest plastics – and one of the most electrically conductive materials – effectively as conductive as copper. Heat-resistant plastics such as polyimide (PI) are substantially more expensive and they are not conductive. Similarly, stainless steel is substantially more expensive (especially as electronic-grade material with smooth surface finish) and not sufficiently conductive to be useful as a conductor. The following table summarizes the key material properties of the main possible choices for CIGS-on-foil processing:

		Al	Cu	Ti	SS	PI
Resistivity	uOhm-cm	3.3	1.7	>100	60	1E+10
Cost	$/sqm/2mil	0.3	>10	>>10	>10	10
Web Width	mm	1500			1000	

Figure 2: Characteristics of several candidate materials for solar-cell substrate foil: aluminum, copper, titanium, stainless steel, and polyimide.

Aluminum is easily smoothened, whereas this is expensive with steel; and aluminum is available in a web width of 1500mm, or 50% wider than the maximum width available for smooth stainless steel. A smooth surface finish is indispensable for creating thin-film solar cells with high yield. Web width in turn drives production capital efficiency and material utilization, especially with sputtering tools.

Most importantly, though, the conductivity of aluminum allows it to be used to carry the current of a solar cell with negligable resistive loss. This fact enables substantial materials cost and equipment capital-expenditure savings on thin-film cell production.

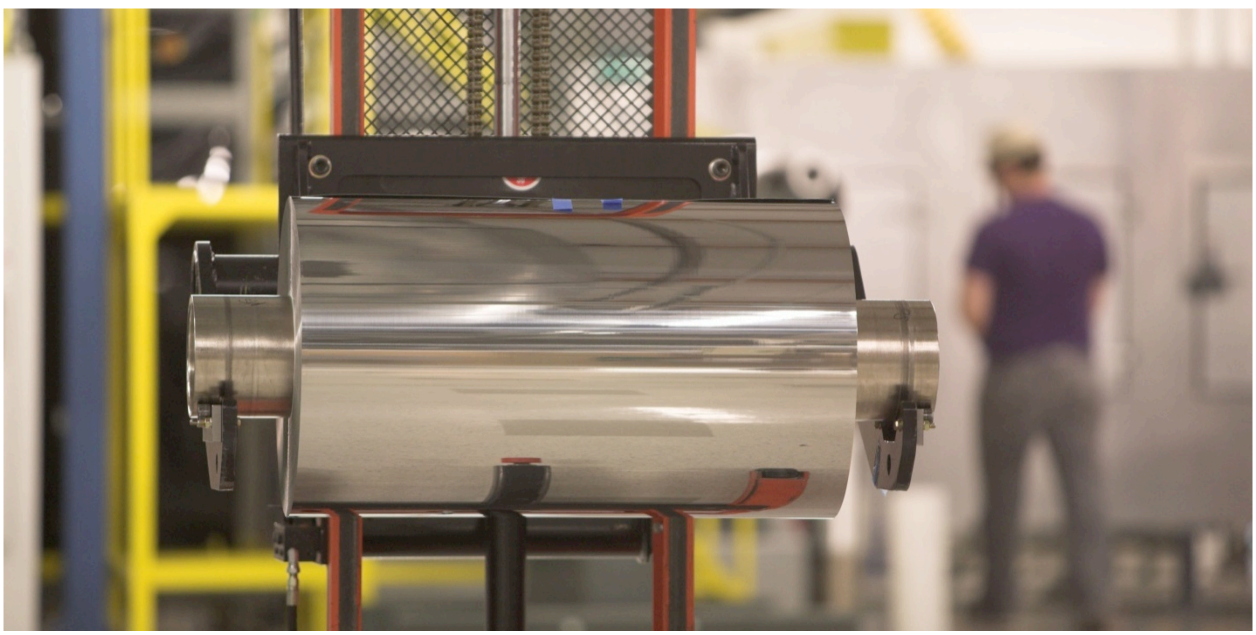


Figure 3: Nanosolar uses a proprietary low-cost alloy of highly conductive, wide-web aluminum foil.

The result is that everyone would use aluminum – if they could. But many groups around the world have intensely tried to make aluminum work as a solar-cell substrate – and failed. The main reason turns out to be that the high temperatures and other process conditions intrinsic in the use of a high-vacuum process for depositing CIGS (as used by most every group) are fundamentally not compatible with the use of aluminum.

At Nanosolar, we have succeeded in making aluminum foil work as a substrate for CIGS and roll processing. We are using a proprietary aluminum alloy optimized for conductivity, web handling, and electronic-grade surface finish. This required the entire process sequence and associated tooling to be developed to be compatible with aluminum as a substrate and involved reinventing almost every process step for this unique capability. The result, however, is a vast cost and capital-requirement reduction.

Nanosolar CIGS-on-Aluminum versus State-of-the-Art CIGS

Nanosolar's use of aluminum as a conductive foil substrate makes it possible to use the material as a conductor for the current generated by the solar cell. This minimizes the necessity of that function to be carried out by an expensively deposited thin film of material (molybdenum in the case of CIGS), enabling a distinctly more cost and capital efficient thin-film cell stack.

The following figure compares a conventional, state-of-the-art CIGS cell stack with Nanosolar's design which, in addition to the non-vacuum (printed) CIGS semiconductor, features substantially reduced thicknesses of electrodes due to the use of aluminum as a substrate as well as due to the Metal-Wrap-Through architecture (see below) employed.

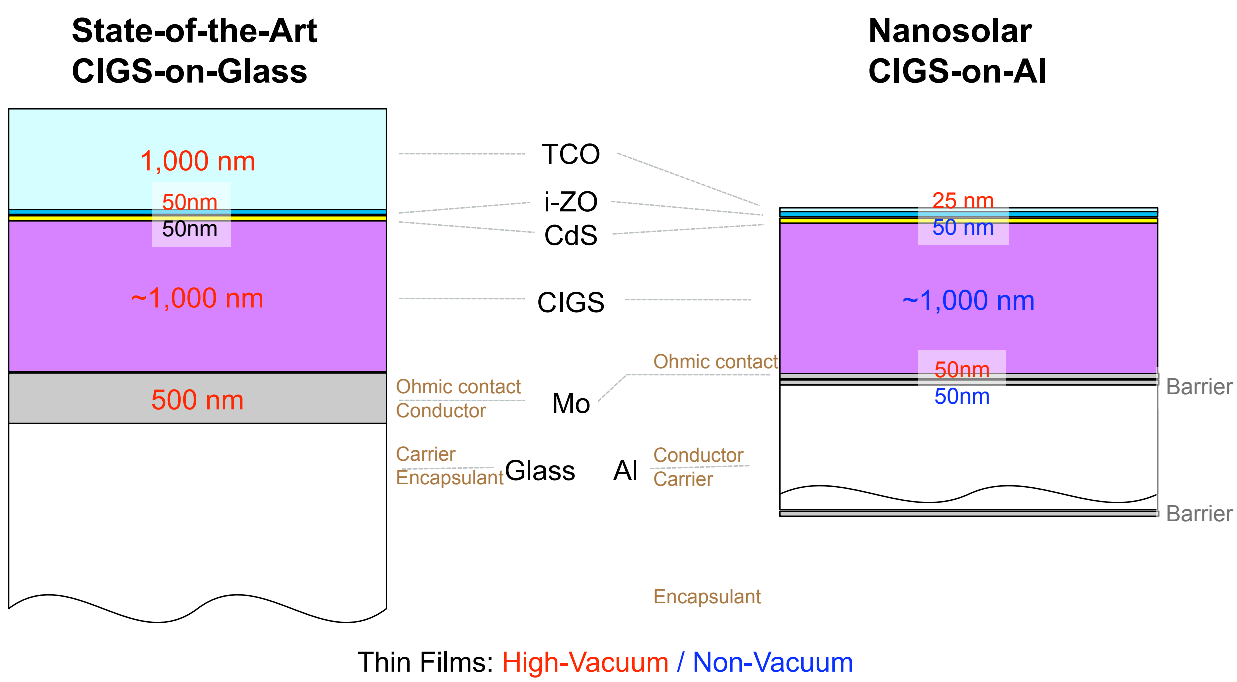


Figure 4: Comparison of State-of-the-Art CIGS versus Nanosolar's CIGS-on-Aluminum. Thickness numbers in red indicate depositions using a high-vacuum deposition technique. The state-of-the-art stack requires close to 3000nm of high-vacuum processing whereas Nanosolar's stack requires less than a tenth of that.

Our cells are processed with molybdenum bottom-electrode films as much as ten times thinner than required with a thin-film-on-glass approach (where the bottom-electrode film has to be thick enough to carry all of the current since the glass cannot carry any). This implies an order of magnitude cost reduction on the bottom-electrode component of the solar cell, a major capital-expenditure sink otherwise. Note that the difference between a 500nm thick film and that of a 50nm thick film is equivalent to the difference of $200 million versus $20 million spent on tooling – for equivalent production capacity.

Nanosolar Advantage	Capital Efficiency	Materials Cost
Molybdenum	10x	1/10th
CIGS	100x	1/2
TCO	5…10x	$1/10^{th}$…1/5th

Figure 5: Capital and cost efficiency advantage of the Nanosolar CIGS-on-Aluminum stack for the key thin films of a CIGS cell (bottom electrode, absorber, top electrode). The materials cost advantage on the CIGS absorber is due to the high materials utilization of the printing process.

Printed CIGS

Nanosolar has developed proprietary process technology to simply print the semiconductor of a CIGS cell. Printing is the fastest and simplest method conceivable for depositing a thin film of material; the capability to employ this atmospheric wet-deposition technique without the need for clean-room condition for solar-cell processing is obviously a game changer – if one can get it to work.

Even though CIGS is a well-known photovoltaic semiconductor, the requirement of four chemical elements rather than one leads to significant process technology challenges which have so far prevented it from delivering on the promise of truly low-cost solar electricity that has motivated three decades of world-wide research and development into this semiconductor. Specifically, for the reproducible formation of an efficient CIGS cell, it is critical that the atomic ratios ("stoichiometry") of the four elements of its semiconductor are in a certain exact target ratio relative to each other. Furthermore, this stoichiometry must be reproduced across the entire area of the cell at each and every length scale.

Conventionally, high-vacuum based processes (evaporation or sputtering) have been used to deposit the elements that make up the CIGS absorber. While such techniques can be effective in small-area deposition zones, they are difficult and expensive to scale to larger-area deposition and higher process throughput. High-vacuum deposition processes can achieve the required precision only with expensive and speed-limiting controls and monitors. Laboratory-scale cells can thus be very deceptive in that extension to large areas may range from difficult to impossible. Furthermore, high-vacuum based processes require unavoidably high capital expenditure per unit area and unit thickness of deposition.

Maintenance is also a challenge with high-vacuum systems: they require frequent cleaning of the vacuum chamber walls, associated with frequent interruption of production, in order to avoid contamination of the device by flakes from the walls. Note that material utilization of a high-vacuum process tends to be as little as only 30%, that is, for every incoming gram of Indium for instance, only 0.3g makes it into a cell. In contrast, at Nanosolar, we have demonstrated as part of a Solar America Initiative milestone verified for the U.S. Department of Energy that our end-to-end Indium materials utilization can be higher than 95%.

Printing has a clear advantage over high-vacuum based deposition in terms of materials utilization, stoichiometric uniformity, robustness, and throughput. Printing processes, especially when implemented in a roll-to-roll processing framework, enable up to three orders of magnitude higher throughput for the same production capital invested.

Furthermore, there is a yield advantage in CIGS for the use of printing: the stoichiometric ratios of the various CIGS elements can be effectively "locked" into the ink, ensuring that the right atomic ratios of elements are present at each location, in fact even regardless of any slight film thickness variations.

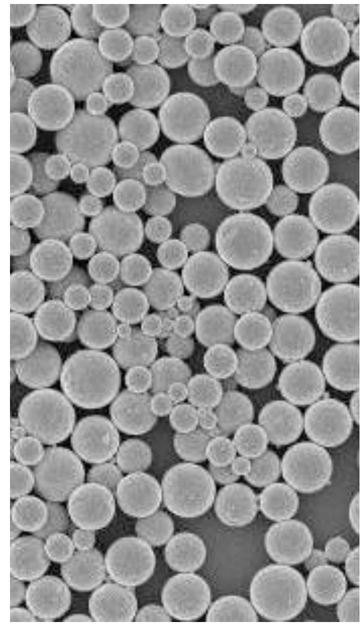



Figure 6 and 7: A laboratory sample of our nanoparticle ink. Nanoparticles shown to the right are an average of 20nm in diameter.

Our team has developed proprietary types of nanoparticles (and methods for cost-efficiently creating them with high-yield bulk creation techniques and low-cost precursor materials), proprietary organic dispersion chemistry by which these nanoparticles can be dispersed into a readily printable ink, and proprietary rapid thermal processing technology to convert the precursor layer into a high-quality, dense semiconductor film with minimal thermal budget.

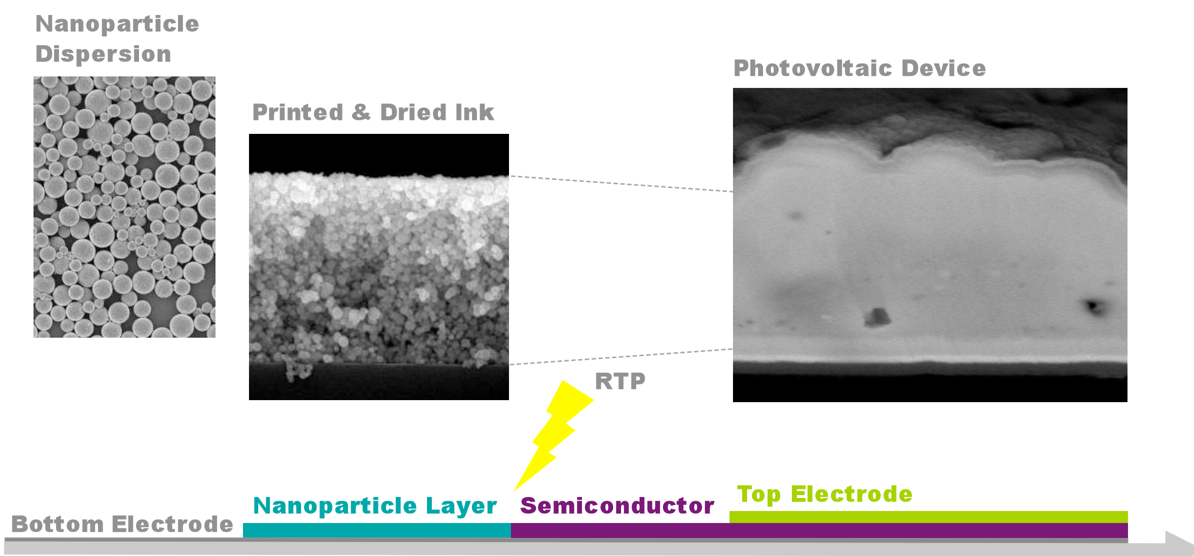


Figure 8: The basic process sequence consists of creating a high-quality dispersion of nanoparticles suitable for high-quality wet coating and converting the printed layer into a high-quality semiconductor using Rapid Thermal Processing (RTP). The art consists of doing so in a way that the resulting semiconductor is indistinguishable in electronic and crystalline quality from one deposited with far more expensive high-vacuum deposition techniques.

The challenge of the printing approach lies in producing a high-quality wet coating achieved by dispersing the nanoparticles into a stable (non-settling, non-agglomerating) solution, which requires extraneous molecules. Yet these extraneous molecules need to be rapidly eliminated during the formation of the semiconductor so that electronic-grade purity is achieved. Our requirement had been from the beginning that we would not use low-cost printing unless the resulting semiconductor was fundamentally indistinguishable from one deposited with (far more expensive) high-vacuum deposition techniques.

Prior dependence on high-vacuum thin-film deposition was primarily due to its ability to produce controllable, high-quality crystalline structures and interfaces for inorganic materials that are normally not susceptible to solution coating. Only by precise and previously unknown control of the nanoscale structure and chemical state of the semiconductor precursor in an ink has it been possible to use solution deposition.

The development of our proprietary semiconductor ink is fundamental because it reproducibly yields high-quality dense films with the stoichiometry necessary to achieve efficient cells. The result is quite remarkable: An inexpensively printed yet high-quality semiconductor whose process of deposition intrinsically exhibits superior area uniformity compared with more expensive deposition techniques.

Prior to identifying our own, internally developed approach at Nanosolar, in 2003 and 2004, we investigated a broad range of avenues for printed CIGS. This included chemistries and processes based on partial-oxide spray pyrolysis (for which we licensed patents US 6,268,014 and US 6,821,559); metal oxides (discarded due to long oxide reduction required and difficulty of including Gallium); organometallic precursors (discarded due to high cost); solid-solution nanoparticles (for which we licensed US 7,091,136 and US 7,521,344); metal hydroxides and metal salts (US 2008/0280030); hydrazines (discarded due to lack of manufacturability, with many coat/anneals required and hydrogen selenide generated); high-throughput 3D-ALD (US 7,115,304); to name just a few of the avenues our team considered.

Furthermore, the process of depositing material is only one part of the equation, with the process of rapidly forming a high-quality semiconductor film after materials deposition being a fundamental and challenging technology development as well. Prior work used toxic gases such as hydrides and slow anneal steps to accomplish this, which was an unacceptable choice to us. (Hydrides are highly toxic and OSHA-regulated at the ppm level.)

Figure 9: A Nanosolar roll-to-roll processing tool for rapid semiconductor formation, San Jose, California.

The result of the front-end cell production is a roll of inexpensive aluminum foil with a hair-thick sandwich of thin films on top of it – capable of directly converting sunlight into electricity.

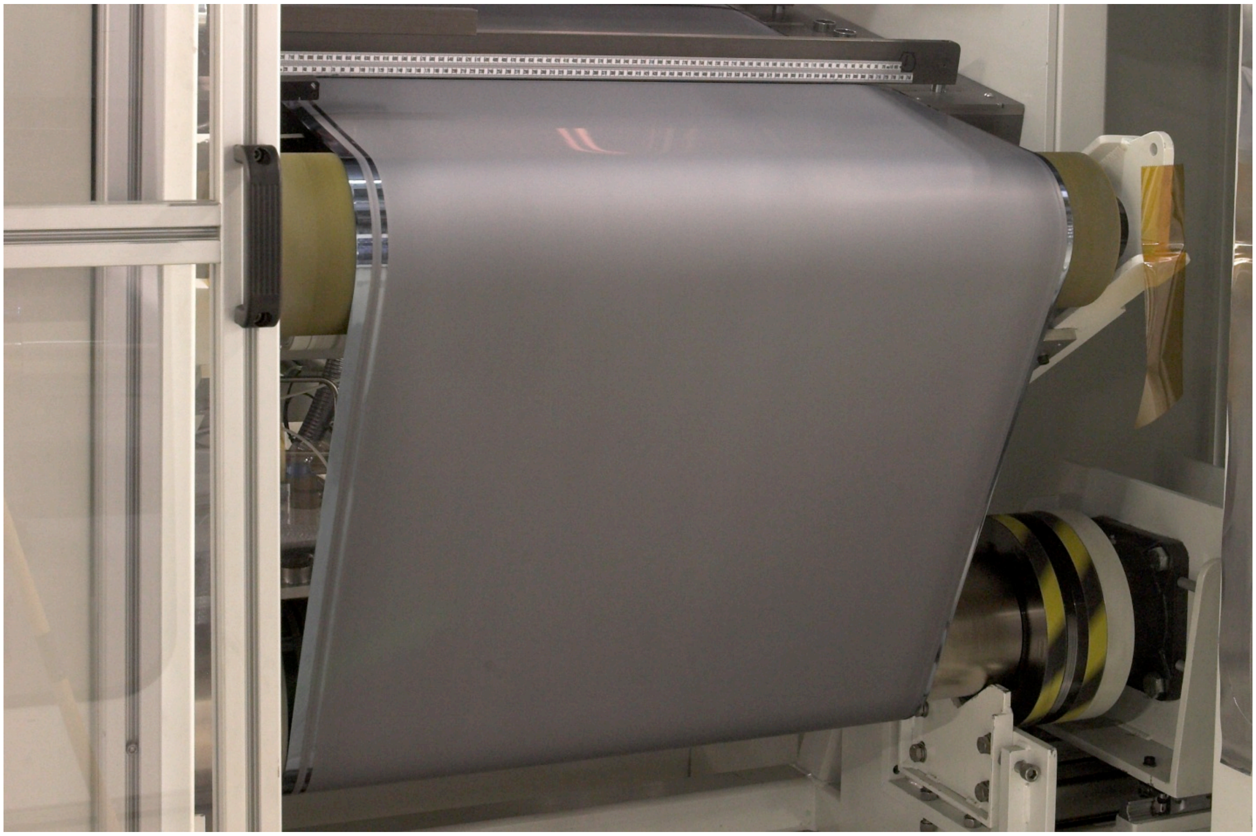


Figure 10: A Roll of CIGS Foil in Nanosolar's San Jose factory. One full roll is equivalent to 100kW, which would be 1,000 glass plates (or 100 carts with 10 plates each) in a manufacturing framework based on glass processing, exhibiting the superior manufacturing footprint that roll processing enables.

Figure 10 is effectively one single huge solar cell on a roll. Such a cell-on-a-roll would have impractical electrical characteristics – a voltage of less than 1V yet a current more than 100,000 Amps. The foil is therefore slit and sheeted into singulated cells that are then assembled into series-interconnected strings and circuits to form a panel with suitable electrical and product-form-factor characteristics.

Pixels sampled on such solar-cell foil measure respectable efficiencies despite the low cost of the Nanosolar process. Figure 11 shows NREL's measurement of such a solar-cell corresponding to a 16.4% active-area efficient cell foil produced with our Gen-3 process.

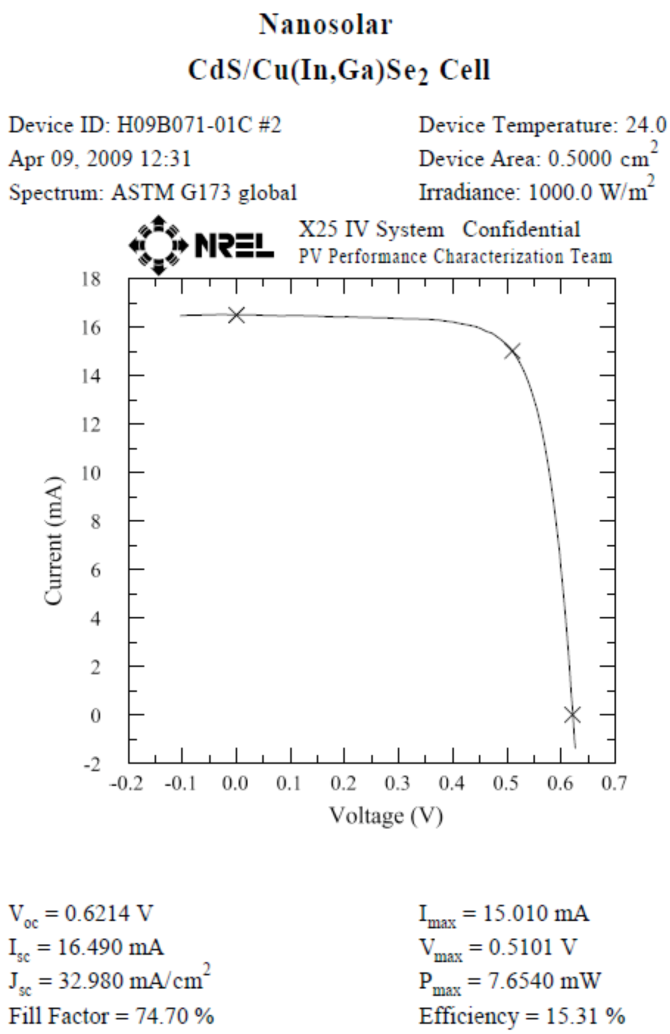


Figure 11: A 16.4% Active-Area (15.3% Total-Area) Efficient Printed-CIGS-on-Aluminum Gen-3-Process Nanosolar Cell Measured by NREL. (NREL's practice is to measure the efficiency of submitted cell samples using a contact grid not used by Nanosolar's MWT back-contact structure. NREL also certified an active area of 0.467cm^2 for the device sample area of 0.500 cm^2. The combination of these two facts allows determination of the active-area foil efficiency at 16.39%.)

Metal-Wrap-Through Back-Contact Cell

Carrying forward our core cell cost advantage towards a finished cell and product, we exploit the uniquely high conductivity of our metal-foil based cells in order to produce a simple yet powerful back contact structure that is uniquely possible with such highly conductive foil.

We have developed the first Metal-Wrap-Through (MWT) thin-film solar cell based on a foil-lamination process. This new approach is particularly cost efficient. Roll-to-roll lamination is a widely employed, simple, and very-high-throughput processing technique. It works specifically (and only) for thin-film solar cells based on high-conductivity foil.

Our work on back-contact thin-film architecture represents by itself an approximately 200-person-year research and development investment and is patented internationally, including through U.S. patents 7,276,724, 2006/0157103, 2007/0186971, 2008/0308148, and 2008/0142073.

In our back-contact cell architecture, electrons are directed from the cell's transparent top electrode through holes onto a low-cost secondary back-side foil, which is a metal foil that effectively acts as a "superhighway" for conducting electrons; this is far superior to any top electrode (given that any top electrode is always facing the difficult trade-off between the simultaneous requirements of high transparency and high conductivity). Best of all, the technology maps naturally onto a high-throughput roll-to-roll processing implementation.

The resulting MWT cells are capable of generating and easily carrying high currents on the order of 6-10 Amps (and up to 25 Amps for cells of the same design sheeted at larger length), which is an order of magnitude more than possible with state-of-the-art thin-film solar cells. (Without a back-contact design, the resistive losses in the top electrode would be prohibitive for any high-current cell.)

The MWT back-contact design reduces losses from reflective grid lines and metal-interconnect ribbons in the front of the cell. It minimizes optical and resistive losses, resulting in relatively higher fill factor and efficiency; and it allows us to create much larger cells than otherwise possible.

Perhaps most significantly though, the design allows us to minimize the thickness of the high-vacuum deposited electrode films by up to a full order of magnitude (reducing materials cost and capital expenditure required by that same factor). It also makes it possible to simply electrically contact each cell at the back; and it allows the cells to be processed quickly and easily into robust circuits for panel products.

The back-contact cell architecture we have implemented is uniquely possible with our aluminum foil based cells; it is not possible with thin-film-on-glass technology. In particular, it makes it possible for us to create high-current panels that minimize utility-scale total-system cost (see the Nanosolar Utility Panel™ White Paper for details.)

The basic process sequence of creating our MWT design is the following:

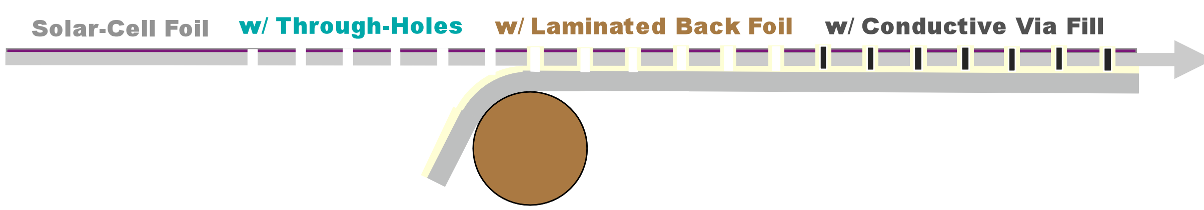


Figure 12: Nanosolar's Lamination-Based Process for Creating a Metal-Wrap-Through Back-Contact Cell.

Step 1: Hole creation. Holes are created in the CIGS foil using a single tool capable of supporting hundreds of MW of annual capacity.

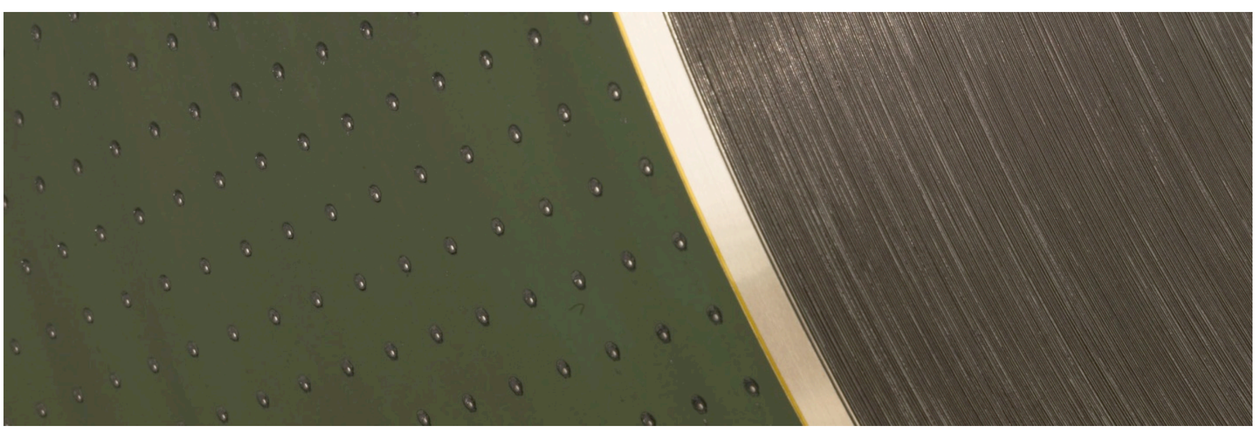


Figure 13: CIGS foil with holes prepared for establishing conductive vias between the cell's transparent top electrode and the backside aluminum foil.

Step 2: Lamination and Hole Insulation. The cell foil is laminated with a secondary low-cost aluminum foil with an insulating adhesive in between. Cells are quality-tested for 1000V of breakdown voltage even though they see less than 1V in voltage in operation.

Step 3: Via Filling. Insulated holes are filled with a conductive paste to create a conductive via. Depending on the top electrode properties, fingers can be printed additionally. A variety of finger pattern designs are possible.

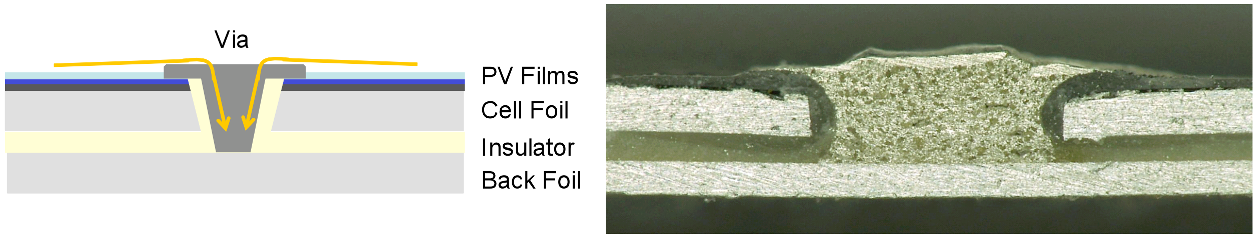


Figure 14: Nanosolar Back-Contact Cell Architecture: Two laminated aluminum foils with conductive vias.

Figure 15: Nanosolar MWT back-contact cells are interconnected into electrical circuits via tabs on each cell that are simply the overhang of one of the two laminated aluminum foils.

The result is a back-contact solar cell that can be easily integrated into circuits and a variety of product form factors.

Efficiencies reached for these cells/panels are comparable with the best panel efficiencies achieved by First Solar in its most recent quarter. Figure 16 shows the NREL-measured IV curve of an 11.3% MWT cell (which would yield an 11% panel) produced with our Gen-2 process; and Figure 17 shows the efficiency distribution of a sample production roll. Unlike with silicon and thin-film-on-glass technology, where there is a distinct gap between cell and panel efficiencies, a solar panel built with our MWT cells has effectively the same efficiency as the MWT cells. This is because a Nanosolar MWT cell already incorporates most of the losses that occur during the cell-to-panel transition, panels are assembled from tight bins of sorted cells, and any additional geometric loss at the panel level is canceled out by lamination gain.)

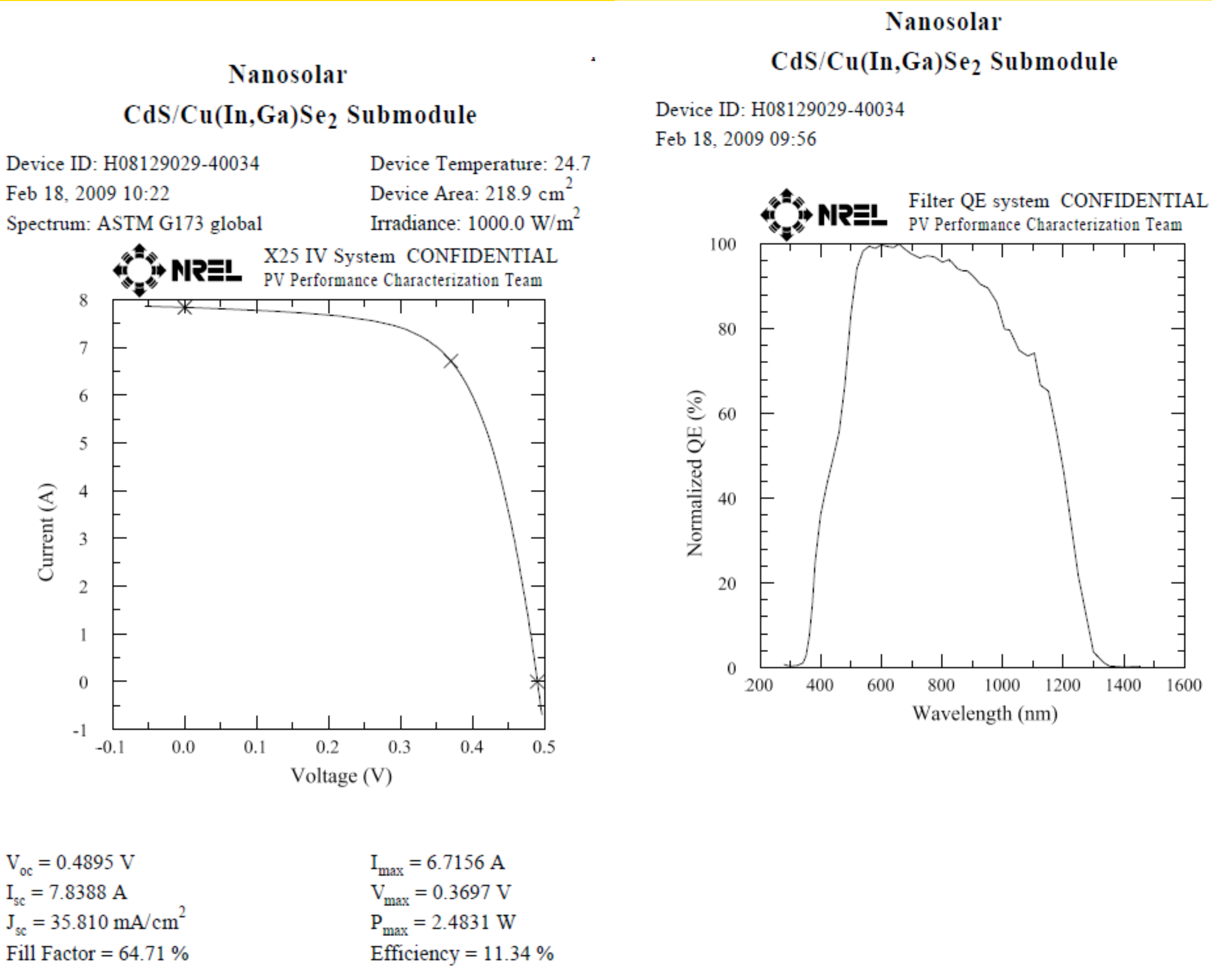


Figure 16: An 11.3% Nanosolar Gen-2-Process MWT Cell (equivalent to an 11% panel) measured by NREL.

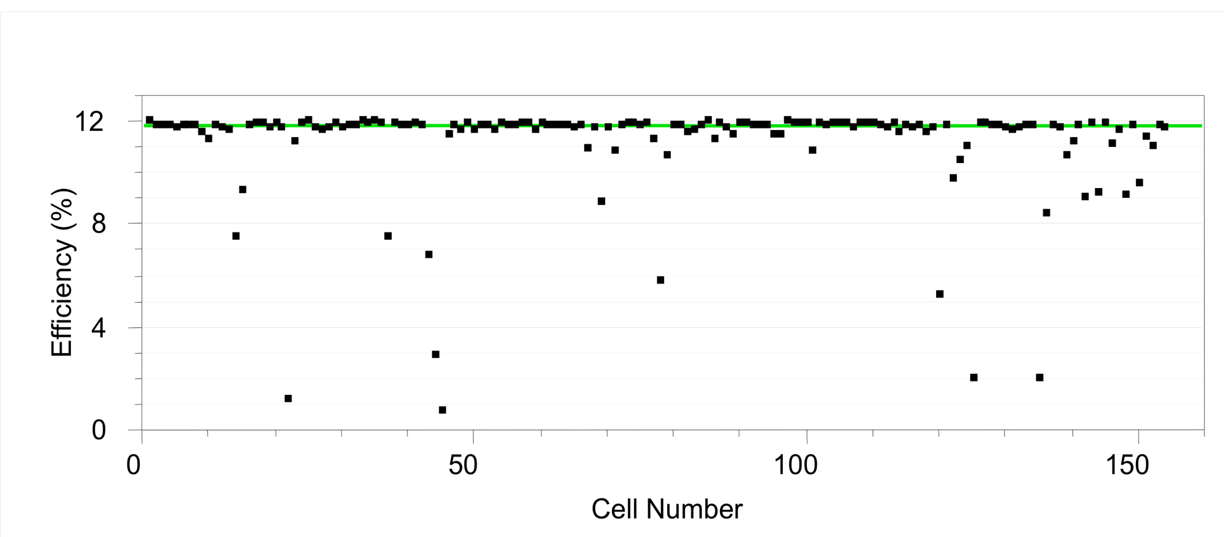


Figure 17: MWT Gen-2-Process efficiencies equivalent to panel efficiencies of a sample roll processed on August 28th, 2009. This run had a median efficiency of 11.75%.

Sorted-Cell Stringing and Panel Assembly

Our thin-film panels are based on assembling individually tested and sorted MWT cells into circuits and then laminating these circuits into panel packages. This is in contrast to the necessity of monolithically integrating cells as required and conventionally applied in a thin-film-on-glass approach. Furthermore, our flexible cell technology enables us to produce a versatile range of panel form factors and rapidly respond to dynamic market requirements without the risk of tooling obsolescence.

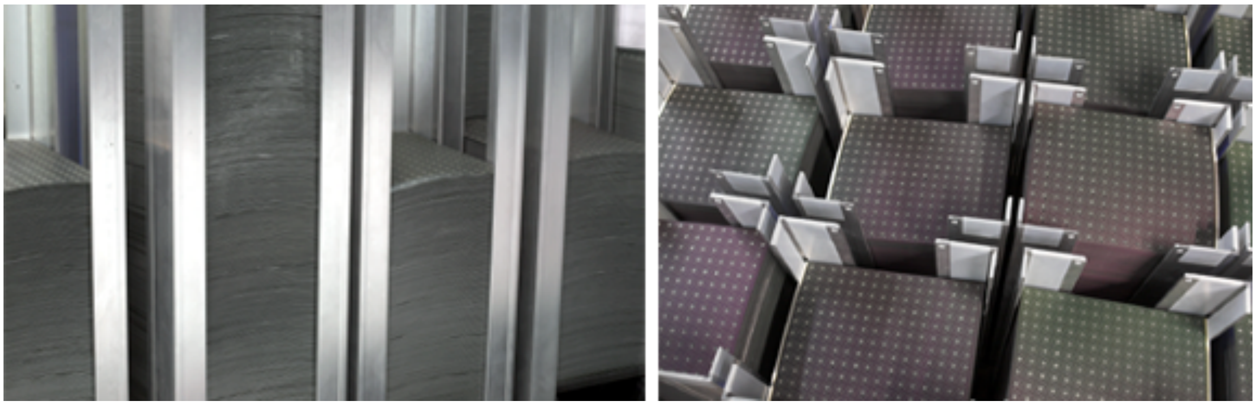


Figure 18: Bins of Nanosolar MWT Cells: Cells are sorted into bins according to electrical characteristics.

Cells are strung into circuits by connecting aluminum foil to aluminum foil—a robust and reliable interconnection that does not require any transition materials and thus avoids a large body of conventional failure mechanisms.

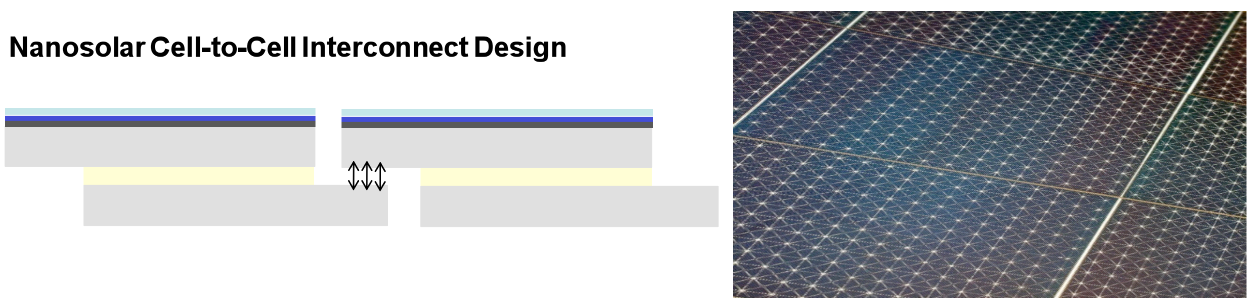


Figure 19: Nanosolar's cell-to-cell interconnect design is fast to assemble and robust in quality because it does not involve a transition in materials, a common source of failure.

By matching the electrical characteristics of cells before they go into a panel, exponentially smaller mismatch losses are achieved, allowing higher panel efficiency for a given cell efficiency distribution and creating more highest-efficiency "premium" panels while minimizing the dollar-value yield-loss impact of bad cells.

With the bulk of a panel's material cost being in panel components other than the cells (once cells are as low in cost as ours), it is a significant advantage in cost-efficiently ramping manufacturing to high yield if one can cheaply discard bad cells and ensure that high-cost components (such as glass) are only applied towards the end of the processing sequence in very-high-yield process steps.

In addition to the relatively lower panel yield, monolithic integration is also prohibitively costly during initial manufacturing ramp when cell yield is still to be improved; or said differently, cost-capped manufacturing ramp with a sorted-cell assembly approach can be much faster.

We have simulated the difference in panel efficiency distribution that results from applying our sorted-cell assembly approach versus applying monolithic integration assuming the same cell efficiency distribution in each case: The basic effect is that, in a thin-film-on-glass panel approach, a bad cell tends to result in the entire panel being an expense hit whereas, with a cell-sorting approach, only that cell will be a yield-loss expense. The value impact of that difference is staggering: If a panel contains 100 cells and the cells together have half the direct cost of a panel, cell sorting lowers the yield-loss expense of a bad cell from 100% to 0.5% of the cost of a panel. Conversely, in order to have a tight, high-yield panel efficiency distribution for monolithically integrated panels, the incoming cell distribution has to be extremely tight to be economic.

Summary

In this White Paper, we described the product of our investment in developing an ultra-low-cost photovoltaic cell based on an innovative technology platform. We believe the result will set the standard for cost efficiency in solar electricity cells in today's industry.

Technical accomplishments include the development of

- the industry's most efficient printed solar cells (16.4% active-area efficiency);
- the industry's most efficient solar cell on low-cost aluminum foil (at almost three times the efficiency of any other cell ever produced on this substrate);
- the industry's thinnest electrode thin films of any thin-film solar cell (at up to an order of magnitude thinner);
- the industry's first back-contact thin-film solar cell based on simple high-throughput roll lamination;
- the industry's highest-current thin-film solar cell (and the straight-forward capability to produce cells with more current than any cell on the market today);
- the industry's most capital-efficient manufacturing process.

We believe we are only at the very beginning of the potential of our technology platform and see more opportunities than ever based on the manufacturing processing we have established.