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Cost of Ownership for c-Si Front & Back-Side Metallization Processes

With this edition of Applied Cost Modeling, we are publishing the first installment in a series on the application of cost of ownership (COO) and overall equipment efficiency (OEE) to crystal silicon-based (c-Si) photovoltaic (PV) metallization.

Introduction[1]

This paper, the third in a series covering cost of ownership (COO) studies for photovoltaics, examines the need for metallization of silicon-based solar cells and how it has evolved over the past few years. We also look forward, to the technologies and techniques that are being developed for this part of solar cell manufacture in the foreseeable future. The paper will conclude with a COO case study using the DEK Solar PV3000 as an example.

Solar Cell Production Outlined

Metallization is the final step in the solar cell manufacturing process and, as such, its success depends very much upon the steps that precede it. A discussion of metallization and its development must, therefore, take into consideration the entire solar cell production cycle. So before we describe the process of cell metallization it is worth first outlining the entire process through which the silicon wafer travels on its way to becoming a fully fledged solar cell.

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Calendar of Events

September 2012

25-28 **EU PVSEC**
Messe Frankfurt
Frankfurt, Germany

October 2012

3-5 **PV Taiwan**
World Trade Center
Taipei, Taiwan

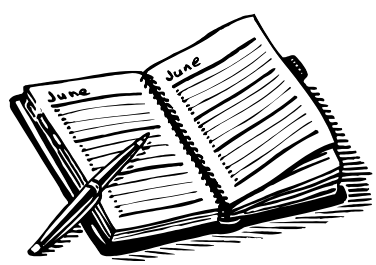
9-11 **SEMICON Europa**
Messe Dresden
Dresden, Germany

November 2012

3-5 **International Conference on Renewable Energies for Developing Countries**
Hotel Comodore
Beirut, Lebanon

December 2012

5-7 **IEEE International Electron Devices**
Hilton San Francisco
San Francisco, CA



Firstly, the silicon wafer is sliced from a monocrystalline or polycrystalline silicon ingot. This step can be carried out either directly at the silicon foundry or by the solar cell manufacturer. The sliced wafer then goes through four distinct manufacturing steps, finishing with metallization, after which it is ready for mounting into a solar panel.

The first step in the cell manufacturing cycle is wet etching, which is described in depth in the second paper in this series.[2] Here, the imperfections created in the sawing process are removed, then the wafer's surface is texturized to create the microscopic pyramid structures that will enable it to trap and absorb sunlight rather than reflecting it.

Described in the first paper in this series[1], the second step is a thermal diffusion process whereby an n-type layer is diffused through the wafer's top layer and down into its structure. Typically made of phosphorous-rich material, this combines with the wafer's own n-type material to create the cell's p/n junction, a planar semiconductor device that will generate electrical current. During the diffusion process, a layer of glass is created on the surface of the cell that is removed in an additional etching and de-glassing process.

In the third step, the cell's antireflective layer, is laid down in a plasma enhanced chemical vapor deposition (PECVD) process that gives the cell its blue color, after which the cell is ready for metallization.

Metallization Explained

The photovoltaic industry uses screen printing as the method of choice for depositing silver and aluminum onto its solar cells. Inkjet printing, the only commercially available alternative to screen printing, is little used, principally because its use calls for an additional plating process, which adds extra cost and which does not lend itself to the solar industry's in-line production approach.

Today's metallization process typically consists of three separate print phases, two on the cell's back-side and one on the front-side. The order in which the printing is carried out depends upon the manufacturer's operations. In the first back-side print step, silver contacts are printed in the form of two bus bars or, less frequently, in the form of simple tabs. In the second print operation, a thin layer of aluminum is laid down across the entire back side, creating the cell's back-side field, or contact (see Figure 1). In a further print step, the front-side of the cell is printed with a silver conductor grid (see Figure 2).

The aluminum and silver act as the terminals of a battery, routing the electricity off the cell. The electricity is generated by photons of sunlight hitting the cell's p/n junction and releasing electrons that migrate through the n-type silicon to the cell's front face. Here they are captured by the grid of silver conductor fingers and routed through the cell's electrical circuit to the back field, their movement creating an electrical current that generates the cell's electricity. In the meantime, holes in the atoms at the p/n junction that are now without their electrons are in their turn attracted by the aluminum back field, where they recombine with their electrons, and then migrate back into the wafer.

Clearly, the more electrons the silver conductor grid harvests, the more efficient the solar cell, so ideally, we would want to print the conductor grid across the entire front surface of the cell. Unfortunately, this is not possible, as the same grid that collects

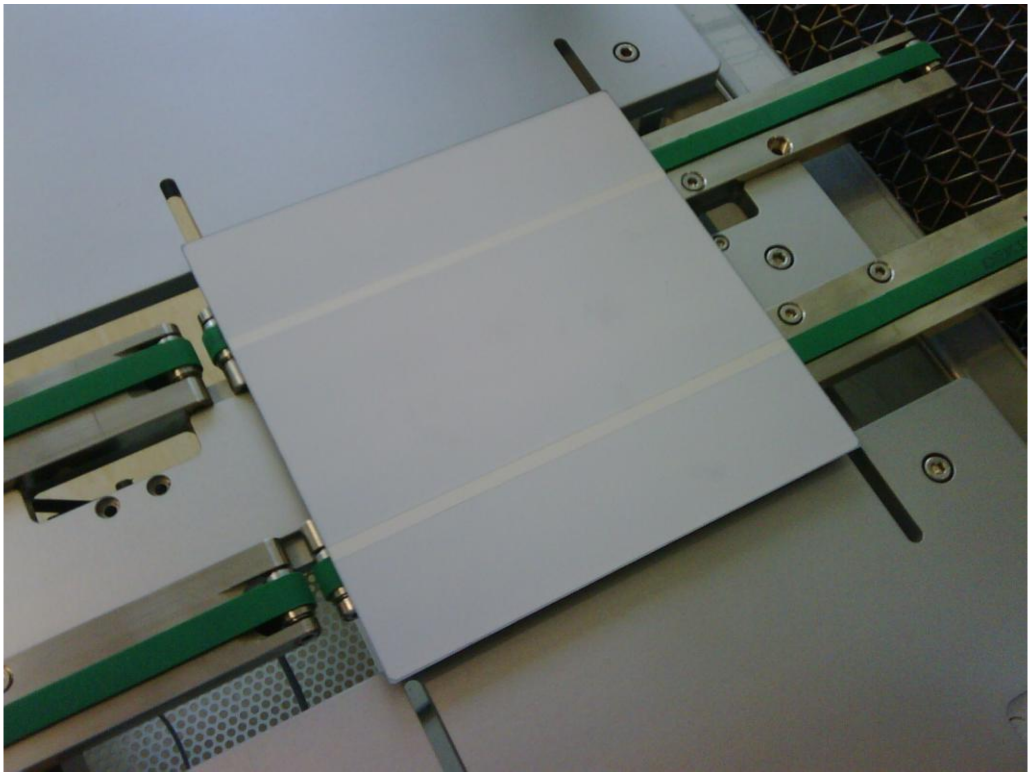


Figure 1: Back-Side Metallization

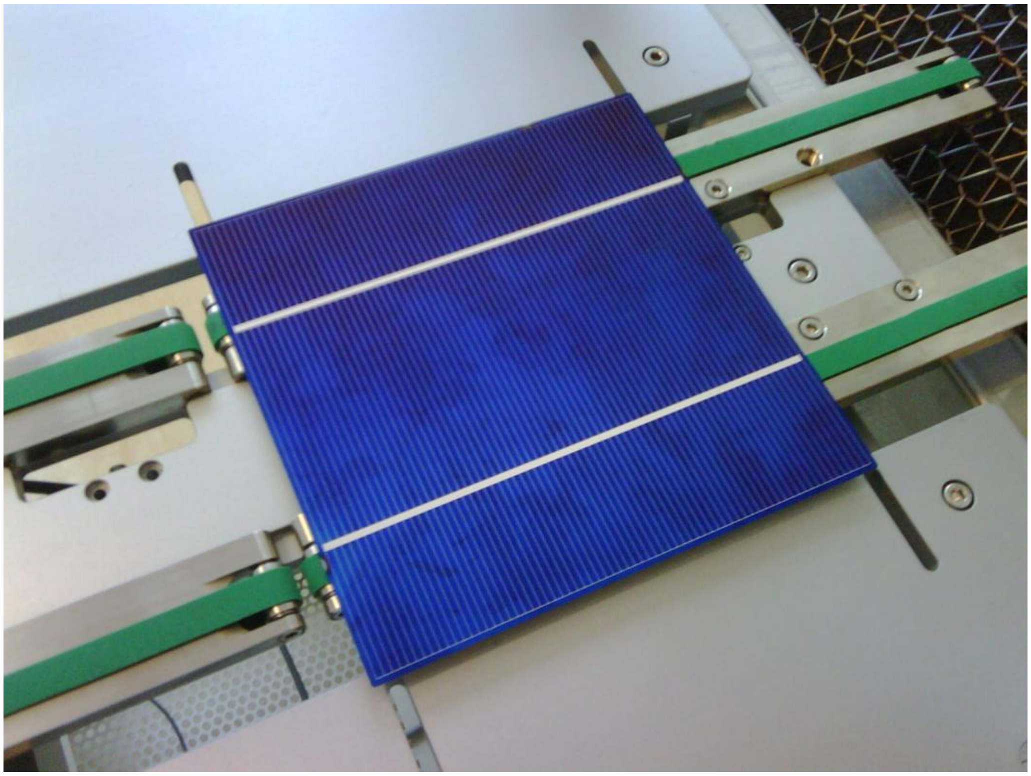


Figure 2: Front-Side Metallization

electrons actually prevents their generation by putting the underlying silicon into shadow. Thus, there must be a trade-off between electricity generation and harvesting efficiencies. The solar industry has access to numerous mathematical formulae that calculate the best grid size and density for any cell design.

Typically the wafers are presented to the metallization line either on a conveyor straight from the PECVD process or in coin stack boxes or cassettes. The first piece of equipment in a metallization line is usually an unloading mechanism and possibly an inspection station that checks the wafers for damage from previous processes. At this point, they will go into the first screen printer, where, on a DEK line, they are loaded singly into a completely flat nest that supports them and holds them down using a vacuum. A camera system is used to align the image on the printing screen with the edges of the wafer, or alignment features or fiducials on its surface, after which the wafer is presented to within 1 mm or so of the screen depending on the print gap.

In some cases, an automatic paste dispensing system will dose the print paste onto the screen prior to the print stroke but often, and especially in lower labor cost areas, this is achieved manually. DEK's equipment uses a print flood process whereby a floodbar, or doctor blade, first spreads a very thin layer of paste across the surface of the print screen, after which the squeegee sweeps across the screen, pushing the paste through the mesh onto the wafer. After the print stroke, the screen and the cell part company and the cell is transferred to an inspection station that will check for print quality and accuracy, alignment, breaks, shorts, width violations, and, in the case of the aluminum back-side contact, voids. It is worth mentioning at this point that, unlike electronics manufacturing, solar cell production does not include rework as a standard process. A few breaks in a solar cell's printed features will, of course, affect its functionality, but not enough to warrant the time and expense of rework. So once the cell gets to the end of the line, it will be tested and graded according to its efficiency. Lower efficiency cells will simply be less expensive and will be sold into less demanding applications.

After print inspection the cell is loaded into a dryer, such as one of DEK's hot air convection ovens, to drive the solvents out of the printing paste, and then it is transported on to the next printing station. Once all three print processes have been completed and the wafer dried, it goes through a sintering furnace that fires the front-side silver through the antireflective coating and into the silicon's n-type layer to create an electrical connection. Here it is essential that the silver is fired to a controlled depth and that it does not contact the p/n junction as this would create a shunt, or short-circuit.

The industry standard beat rate is currently at around three seconds and on a standard DEK printing line this three print process takes around four to five minutes including all handling and inspection operations. It is worth noting here that one cell is printed at a time on all DEK machines, to allow for individual alignment of each cell. This is becoming increasingly important as we will see shortly.

Developments in Metallization

Over the past few years the front end of the solar manufacturing cycle–the etching and antireflective processes–have changed a great deal. Now, those changes are moving down the production line and metallization is up for some major developments, driven by a number of important factors. What follows is a brief description of just a few of these factors and their effects on the metallization process.

Wafer Handling

Until a few years ago, wafer thickness was typically in excess of 300-400 µm. Then, as the solar industry started competing with the semiconductor industry for its limited supply of silicon, efficient ingot use became paramount and we saw wafers come down to 200 µm, then 180 µm in 2009. Today's standard is even thinner at 160 µm and some manufacturers are even considering wafers just 120 µm thick. At the same time, wafers have gone from being 100 mm square to 125 mm square and they are now at an industry standard 156 mm square.

Add to this the general move away from monocrystalline silicon to the more fragile and less expensive polycrystalline silicon and it becomes clear that wafer handling has become more difficult. Today, edge contacting is absolutely prohibited and, therefore, so are edge grippers and the practice of driving a cell into a hard stop for alignment. This means that we can only use vision and sensors and the wafer is picked up from the underside or is moved on belts. Indeed, we are now at the point that the only time that the wafer is put under stress is during the print stroke–and development work is underway to improve this issue as well.

Feature Size and Repeatable Accuracy

When DEK started its involvement with the solar cell industry some 30 years ago the widths of the features being printed were up to 200-300 µm. Now, as a direct consequence of the need to reduce the shadows cast by the cell's front-side silver-conductor fingers, print features have become progressively finer over the past few years. The industry has, accordingly, seen line widths shrink from a standard of around 150 µm three years ago to 120 µm in 2010. Some of manufacturers are even looking to achieve sub-100 µm features. The inherent challenge in this degree of miniaturization is to ensure that the conductors lose none of their current-carrying capacity and, so, it is imperative that if they are to be printed narrower, they stand higher. A whole new set of technologies are being developed that allow high aspect ratio grid features, but these demand extreme precision from the printing process. Print-On-Print, for example, allows manufacturers to print ultrafine silver conductor lines twice, but this calls for a highly accurate and repeatable printing process.

Selective Emitter technology, too, resolves the problem of shadowing by depositing extra n-type dopant in a pattern mirroring that of the collection grid. Thus, like Print-On-Print, this requires a second front-side printing operation in the metallization line that will enable both print patterns to be aligned with each other to within a few microns. The added challenge here is that the dopant, the first pattern to be deposited, is invisible, normal vision alignment systems cannot be used to align the subsequent silver collection grid pattern to it. Most manufacturers, therefore, use two small 0.5 mm diameter fiducials, printed at the outer extremes of the cell, to which both deposition processes must be precisely aligned.

As can be seen, in just a few short years the industry has gone from fairly wide features and noncritical alignment requirements to today's ultrafine features, which must be accurately registered to either internal and invisible parameters or to previously printed patterns.

A further route to increased efficiencies is to move the relatively wide bus bars from the front of the cell to the rear, connecting them to the collection grid by means of metal wrap through holes, solar's more complex version of the electronics industry's plated through holes. This too relies on high print alignment accuracy and repeatability.

Print Throughputs

Print throughputs have increased enormously but, at the same time, so have other demands that, on first glance, are incompatible with today's increased speeds. Five years ago solar cell manufacturers mainly focused on throughput because they were dealing with thick, fairly stable wafers. As wafers started becoming thinner, the focus changed to include yield and breakage and now features have become so fine and technologies have changed so much that accuracy is paramount. Speed, yield, throughput, accuracy, and now equipment footprint are the parameters that guide equipment design and development. Concerned that increased print speeds could result in increased wafer damage and decreased accuracies, DEK has developed its PV3000 printing line (see Figure 3) to increase throughputs threefold without increasing the speed at which the wafer is printed. It has achieved this by tripling the number of printing heads at any one printing station, allowing three cells to be printed at the same time and effectively reducing the line's beat rate from three to just one second per cell.

Printing Pastes

Other areas where the metallization process is transforming fast is in pastes and screens. Pastes are typically made of silver or aluminum together with the binder complexes and solvents that render them printable and, in the case of front-side silver print pastes, the glass frit that allows the silver to fuse down into the silicon during the cofiring process. Pastes for front side printing are exclusively based on silver while the back-field pastes are based on aluminum. The pastes used to put the silver contacts on the back side, on the other hand, are often a mix of the two as the silver lends solderability while the aluminum creates an electrical contact. There is considerable concern around the future availability of silver. The cost of silver in comparison to other conductors such as copper is fuelling development work around other less expensive alternatives, but no viable alternative has yet been identified.

Work has also been going on for some time on transparent and semitransparent conductor materials such as Indium Tin Oxide (ITO) that could eliminate the problem of shadowing. The problem at the moment is that in order to achieve the electrical properties required the material must be applied at a thickness that renders it opaque. Some manufacturers are studying the possibility of printing hybrid conductor grids using a thin layer of transparent conductor and a reduced number of silver conductors.

In the meantime, the standard off-the-shelf pastes of five years ago have been tuned for higher speed printing, faster drying, better rheology for higher aspect ratio features, better conductivity, and even for the way in which, and the depth to which, they fire into the wafer during the cofiring process. This has become particularly important for today's thinner wafers, where the p/n junction sits much closer to the wafer's surface.

Printing Screens

Screen manufacturers have put a lot of work into improving paste transfer properties and, therefore, conductor grid structure and

Figure 3: Integrated Screen Printer and Drying Equipment

efficiencies by reducing the diameter of the wire used in print screen meshes to a current solar industry standard of 20-25 µm. Apart from this, however, little has changed in the last decade in terms of the screens used for solar cell printing.

That is, until now. A long-term study led by DEK's Senior Process Development Specialist Tom Falcon has resulted in the development of an innovative hybrid screen design that combines the advantages of mesh printing screens with those of two-layer electroformed stencils. This enables the repeatedly accurate printing of new, high-aspect-ratio features getting the industry closer to technologies such as Print-on-Print, selective etching, and selective emitter.

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Wright Williams & Kelly, Inc. Forms Healthcare Productivity Division

Mark Allen Stinson, MHA named President of WWK Healthcare

September 5, 2012 (Austin, TX) – Wright Williams & Kelly, Inc. (WWK), the global leader in cost and productivity management software and consulting services, announced today the formation of a new division dedicated to bringing its world-class modeling and simulation software tools to the healthcare industry. Heading up WWK Healthcare will be industry veteran Mark Allen Stinson.

"The Affordable Care Act (ACA) has added tremendous pressure on hospitals with regard to patient satisfaction," states David Jimenez, Wright Williams & Kelly, Inc.'s Chairman. "Most people don't know that up to 5% of hospitals' reimbursements will be based on patient satisfaction surveys. The leading causes of patient dissatisfaction relate to long queues in both appointment scheduling and day-of-service execution. These issues can be solved using the same methodologies currently applied in high-tech manufacturing environments where billion dollar assets must be kept at high utilization rates while minimizing queue times and their impact on overall cycle time and quality."

"It is imperative that our healthcare leaders have the ability to make informed decisions that optimize the patient experience," states Mark Stinson, WWK Healthcare's President. "The effects of the ACA have not begun to reveal themselves. Hospitals will have to deliver more care with even less resources and be subject to the transparent performance benchmarking data already available through the Center for Medicare/Medicaid Services (http://hospitalcompare.hhs.gov)."

"Mark Stinson and I started the first interventional pain center in the Houston Market in Tomball in 1992," remarked Dr. Kenneth Aló, a recognized global leader in the field of pain management. "Mark has since developed and is currently implementing preemptive optimization and efficiency strategies for hospital systems in anticipation of the upcoming healthcare changes. The decision support systems now at his disposal will effectuate meaningful change in healthcare. Those who utilize it will be on the leading edge of decision making rather than reacting to the upcoming chaos about to descend upon the healthcare industry."

With more than 25 years of executive level experience in the private and public healthcare industry, Mr. Stinson has administratively directed all hospital-based clinical, support, and administrative departments. His expertise also includes the research, development, and implementation of market-driven service lines, consolidation/regionalization strategies, Total Quality Management (TQM), safety programs, patient-centered clinical delivery systems, culture change management/stakeholder realignment strategies, and the forging of physician joint ventures.

Before joining WWK Healthcare, Mr. Stinson served as President & CEO of Aware Concepts whose mission was to assist healthcare providers in achieving higher quality and efficiency through system(s) integration, strategic facility planning, and operations improvement.

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Parties interested in contributing to the discussion of healthcare cost reduction and productivity improvement are invited to join the WWK Healthcare LinkedIn group at:

http://www.linkedin.com/groups?gid=4586247&trk=hb_side_g

With more than 3,000 users worldwide, Wright Williams & Kelly, Inc. is the largest privately held operational cost management software and consulting company serving technology-dependent and technology-driven organizations. WWK maintains long-term relationships with prominent industry resources including SEMATECH, National Institute of Advanced Industrial Science and Technology, Semiconductor Equipment and Materials International (SEMI), and national labs and universities. Its client base includes nearly all of the top 20 semiconductor manufacturers and equipment and materials suppliers as well as leaders in nanotechnology, micro electro-mechanical systems (MEMS), thin film record heads, magnetic media, flat panel displays (FPD), solid state lighting/light emitting diodes (SSL/LED), photovoltaics (PV), and healthcare.

WWK's product line includes TWO COOL® for detailed process step level cost of ownership (COO) and overall equipment efficiency (OEE), PRO COOL® for process flow and test cell costing, Factory/Healthcare Commander® for full facility capacity analysis and activity based costing, Factory Explorer® for cycle time reduction and WIP planning, and TCOe™ for energy production project costs (cost/kilowatt-hour). Additionally, WWK offers a highly flexible product management software package that helps sales forces eliminate errors in product configuration and quotation processes.

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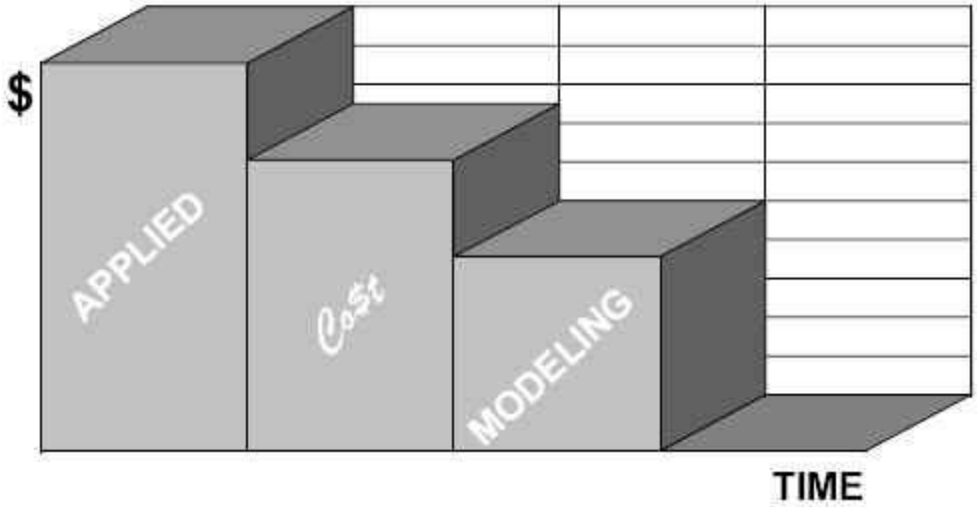
WWK Healthcare Article Published in Texas CEO Magazine

WWK Healthcare has published in Texas CEO Magazine an article titled "The Affordable Care Act and the Patient Experience." The article was released on September 10, 2012 and will be available for viewing at http://texasceomagazine.com shortly thereafter. The main thesis discussed in the article is "…employees and the general public will now have the ability to compare one hospital's scores against another's. Why should anyone tolerate the deplorable lack of signage and endless maze of corridors at our hospitals…?"

WWK HEALTHCARE



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