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Mainstream c-Si metallization process developments and cost reduction strategies

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ABSTRACT

A recent spate of solar cell efficiency gains and record results underline the continued efforts to boost conversion efficiencies, which are at the core of reducing cost-per-watt goals. However, bringing such technology into the mainstream volume production world at little or no increase in manufacturing cost will prove more challenging. This paper takes a look at the current mainstream c-Si cell metallization efficiency developments that are starting to enter volume production with a promise of 20% cell efficiencies and low manufacturing costs.

Although many exciting and novel cell concepts are currently under development, volume cell manufacturers have to take a more cautious route to market, ensuring efficiency improvements are in line with cost reduction strategies. Key concerns also include yield, repeatability, and overall uniformity, amongst others. As many producers are now reaching 1GW+ in annual cell production volumes, being able to integrate new process steps to boost cell efficiencies with minimum disruption and increased cost are vital.

Only a handful of cell manufacturers that are in production have reported c-Si cell efficiencies above 18%. The market leader is SunPower with commercial-scale cell efficiencies now topping 22% with its Gen 2 offering. As recently as June 2010, SunPower announced a new world record – verified by NREL (U.S. Department of Energy's National Renewable Energy Lab) – with a conversion efficiency of 24.2%. The new record efficiencies highlighted that SunPower has been able to increase its cell efficiencies by a full four percentage points over the last five years.

While SunPower may claim the highest commercialized cell efficiencies, its relatively low production volumes (398MW in 2009) and high manufacturing costs – relative to its mainstream rivals – highlights the challenges many manufacturers could face should they pursue a similar technology route.

SunPower claimed that its goal was to see the cost per watt reduced by more than 35%, from approximately US$0.85/W to less than US$0.55/W in 2014, when the fab is fully ramped. These manufacturing lines are expected to be producing SunPower's Gen 3 cells by then, with industry analysts projecting US$1/W by 2014.

Concerns were also raised this year with Suntech's difficulties in ramping its proprietary 'Pluto' cell technology with 19% cell efficiencies, even though it was developed so that it could be retrofitted into existing manufacturing cell lines. The company had stated in the first quarter of 2010 that it was limited to a 4MW per month ramp rate, far below its own previous ramp projections. Suntech is said to be using copper rather than silver paste contacts.

Standard cell developments: front side

Significant effort is being focused on conventional or 'standard' cells via technologies that can be introduced into volume production at low cost and yet incrementally boost cell efficiencies. Not surprisingly, various 'low-hanging fruit' approaches are proving popular.

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As the front-side conductor is responsible for absorbing light and generating most of the electrical carriers, migrating to ever-smaller line widths can boost cell efficiency, enabling a larger surface contact area. A shallow emitter will also reduce shading on the front side, also improving absorption.

Work has been ongoing to provide low contact resistance while obtaining high conductivity, especially on larger substrate sizes. However, this requires improved paste characteristics to achieve improved cell efficiencies.

The Photovoltaic Business Unit of Heraeus has recently developed a new front-side silver paste (SOL9235H) that is cadmium-free and claimed to offer higher efficiencies along with superior contact quality and aspect ratios on both mono- and multicrystalline wafers.

Andy London, Heraeus's Global Business Unit Manager, noted: "Everyone wants to see higher efficiencies out of the silver paste regardless of the type of cell being produced. This doesn't matter even if it's a high ohmic emitter with a much narrower pressure window, requiring paste to have a wider process window. We develop little variations in the paste for required variations in aspects such as vapour deposition and diffusion for example. But better and better contact resistance is also wanted."

Not surprisingly, London also noted that customers wanted to find ways to reduce the consumption of silver paste and for less expensive derivatives to be developed. Collaborations across multiple areas were ongoing to meet the individual needs of customers that are being dictated by the different cell designs and process requirements. He also noted that matching R&D efforts with customer needs is a key ongoing endeavour, especially with five or six different cell approaches – and that's just in the mainstream.

London believes standard cell efficiencies could be at 20% by the middle of 2012, given the current paste and process developments. He was also quick to reiterate that developments in furnaces and screen printers had contributed considerably to these efficiency gains led by tight distribution characteristics.

"We have customers in production right now that have cell efficiencies of 18.8 and above with distribution above 19%. Looking back only 18 months, cell efficiencies were no more than 16%", added London. "We feel we have contributed in that movement to higher efficiencies."

Optimized for high-throughput processing, Heraeus introduced the SOL953, which provides fine line (80–150μm) resolution. It is designed to easily penetrate the SiN_x:H anti-reflective coating during the firing process and provides low contact resistance. SOL953 can be co-fired with commercially available backside Al and Ag/Al pastes. Heraeus claims that customers who tested this new front-side paste during the development and scale-up phase reported increases of cell absolute output efficiencies in the 0.2 to 0.4% range.

Further developments in narrower line widths are ongoing. Heraeus is seeing lines of 20µm and below being printed in the lab, but a key challenge is repeatability and speed for high-volume applications. London explained that as the lines get narrower, the aspect ratio needs to get higher as conductivity of the line will control the efficiency.

"It would not be possible to obtain shallow emitters currently in use without the developments achieved with solar pastes, in particular our PV 159 offering", commented Patrick O'Callaghan, Global Technology Manager, DuPont Microcircuit Materials. "Now we see reducing contact resistance on the wafer is a very important issue for customers as narrower contacts are required. We have therefore continued to advance the technology on aspect ratio and contact resistance, particularly over the past five years."

> "The industry wants a 20% cell using conventional tools and processes before more 'exotic' steps and cell designs are really required."

O'Callaghan noted that with high aspect ratio printing, a thick print in one pass is now possible, which allows for lower grid line resistance due to additional metal deposited. The increased lay-down allowed for finer lines, leading to an equivalent usage and improved cell efficiency. He added that many customers are now printing 70µm finger lines.

DuPont's recently introduced Solamet PV16x series photovoltaic metallization pastes are claimed to provide up to 0.4% greater efficiency. The enhancements are achieved through advanced chemistry which provides lower contact resistance to the Si, as well as via reduced bulk resistivity of the paste, which yields higher gridline conductivity.

According to O'Callaghan, the industry wants a 20% cell using conventional tools and processes before more 'exotic' steps and cell designs are really required. DuPont has a roadmap employing an arsenal of developments that it hopes could meet this need for the mainstream sector of the industry. The most promising concepts for rapid adoption are selective emitter, N-base technology, rear-surface passivation and back-side metal contact technologies. Although these require new steps, they retain conventional tool technologies. The company's new front-side thick-film technologies include the following characteristics and applications: lower contact resistance pastes (0.3-0.5%); lower grid-line resistance; high aspect ratio printing (0.2-0.3%); double printing (0.3-0.4%) and improved fine line capability (0.3-0.5%).

Selective emitter double printing

There appears to be little rush to replace screen-printing, a much-proven technology with the ability to deliver high precision alignment, low breakage rates while operating at high wafer throughput levels. The move to selective emitter double printing is an attractive path that cell manufacturers want to tread.

A selective emitter addresses the blue light response of the cell. Changing the profile with lower surface doping concentration can generate meaningful efficiency gains.

In order to keep losses caused by series resistance low, fine-line printing is required to produce a denser grid of fingers if shading losses are to be avoided, a process that is carried out in two steps: thin seed layer printing and the subsequent light-induced silver plating step. Improvements in screen-printer alignment in recent years are key contributors to the adoption of this emitter design.

Another advantage of double printing is that it gives the silver metallization paste suppliers the opportunity to optimize for both steps, rather than making the necessary compromises required with a single printed thick paste.

"The first print needs to be as narrow as possible requiring excellent contact resistance. The advantage of double printing from a paste perspective is the ability to optimize the paste just for contact resistance characteristics. With the second contact print, as the paste is going onto a dry film, very little spreading results, delivering a very smooth print and a film that is optimized for conductivity", remarked Heraeus' London.

"With the bus bar and finger line processes separated, further optimization of the material can be achieved", added DuPont's O'Callaghan. "We will very soon be launching pastes specifically optimized for double printing. If done in the optimal way, double printing could give between 0.3-0.4% in efficiency gain."

However, companies such as Applied Materials with its Baccini-based Esatto platform have claimed as much as 0.46% absolute cell efficiency gain with double printing, data gathered directly from customers' evaluation work with the technology. Indeed, Applied claims that an extra benefit due to the optimization of metallization pastes is the potential to achieve a 14% reduction in material consumption. They have claimed that the combination of higher efficiency and reduced material expense is projected to lower manufacturing cost by over US\$0.03/W and deliver a return on investment in as little as eight months.

In a production environment, their double-printing technology allowed the replacement of single 120µm-wide lines with two-layer, double-height lines less than 80µm wide on the finished cell with multiple layers of different materials overlaid and better than ±15µm repeatability. Of course, with the focus

Figure 1. Applied Materials' tool box for c-Si efficiency improvements.

on narrower finger lines using double printing, print accuracy is now a key requirement for all equipment vendors.

As shown in Fig. 1, Applied Materials sees a 'tool box' of process improvements that could achieve up to 5% efficiency gains with continuous improvement strategies before the need for alternative technologies.

Dr. Christian Buchner, CEO of Schmid Technology, emphasised the rapid adoption rates, having launched its selective emitter processing technology at EU PVSEC in September 2009. The company has received confirmed orders for 1.5GW of equivalent solar cell production of its technology, which has, the company claims, bestowed the title of selective emitter market leader upon the company due to its simpler wet chemistry processes as part of an integrated line.

"Our research results show that the cell efficiency of multicrystalline wafers has been increased by 0.4% and that of monocrystalline wafers by 0.8%", noted Buchner.

Its cell technology, known as 'inSECT' (inline selective emitter cell technology), is claimed to be easy to integrate into existing manufacturing lines – perhaps another reason for the high interest levels. Throughput of the inSECT line is said to be 2,200/wph.

Only one further process step is necessary to reduce the surface between the subsequent contacts down to a depth of 50nm. The additional processing stage, including investments, consumed materials and amortization costs are claimed to be only €0.08.

However, as pointed out by Buchner, absolute cell efficiency gains using double printing need to be backed up carefully with low production costs to make the technology viable in the mainstream. An important point raised by Buchner about double printing revolved around screen-printer design and its impact on wafer breakage. Doubling the printing steps required taking a second look at wafer breakage as allowing doubling of the average percentage of breakages would raise production costs, negating some of the selective emitter double-printing gains.

"We genuinely believe from all of the manufacturing process data we have collected that screen printing contributes to wafer breakage due to the process touching the cell, either in the line or via the development of micro cracks that cause breakage later such as at the module assembly stage", commented Buchner. "This leads to around half to one percent of wafer breakage; with double printing this had to be addressed which led to the development of a 'touchless' process at Schmid."

> "Absolute cell efficiency gains using double printing need to be backed up carefully with low production costs."

Buchner sees future benefits of this approach when the industry moves to thinner and thinner wafers, though he conceded that it was difficult to predict when this will happen.

Another equipment supplier focused on bringing double print selective emitter technology into the mainstream volume production arena is ASYS Solar. The newest printer in their offering is the XSR1 turntable printer, with a throughput of 1,600 cells an hour and a print accuracy of ±12.5μm @ 6 Sigma. It also incorporates a new vision system specifically designed for recognition of selective emitters, which is part of their ULTRAline metallization lines.

The company's XSR1 machine employs a turntable that can have four integrated processing stations, a combined optical breakage inspection and alignment station for alignment of the cell edge, as well as recognition of selective emitter structures. It also has a print station with automatic screen alignment, as well as an optional station for post-print inspection.

Dr Lars Wende, Vice President Solar & New Technologies at ASYS Group, was keen to highlight the print accuracy levels of their technology. Wende noted that they had incorporated a new vision system specifically designed for recognition of wafers employing the selective emitter, part of their ULTRAline metallization lines. More is to come from the company, with plans for further manufacturing cost reductions in paste and screen-print masks.

"We are working with partners on a range of efficiency and cost reduction strategies, including paste optimization with improved viscosities", noted Wende.

He also hinted at successful collaborations with Asian partners and the use of nanomaterials for metallization, all achievable with their technology offerings. It was interesting to note that Wende did not seem too concerned with wafer breakage issues, noting that even with double printing the company is achieving fewer losses than in conventional systems.

However, according to Darren Brown, Alternative Energy Business Manager at DEK, there are numerous challenges with the migration to selective emitter double printing.

DEK's PVP1200 screen printer, which is capable of 1,200 wafers per hour throughput, is proving popular, as is its PV3000 metallization line. Asian customers in particular tend to seek out high-throughput tools that offer high accuracy and repeatability, attributes Brown said were ideal for double printer applications.

"We are of course double printing at the moment, but excitingly the technology is really only in its infancy", commented Brown. "Bringing accuracy to the screen print process has been a key enabler for print-on-print processes but we are really only at chapter one...a challenge we're all facing in relation to print-on-print is screen manufacture. Producing high-quality precision screens is not a low-cost operation and with twice the number of screens required, consumable costs are an issue. These issues have been amplified with the need to closely match both screens needed for the process, causing issues with image stability."

With a focus on cost reduction of double printing, Brown pointed out that DEK has been working on various approaches to reduce the cost of precision screens. Some unique approaches that have yet to hit the shelves tackle lifetime issues, adding to the company's aim of further reducing manufacturing costs for the technology.

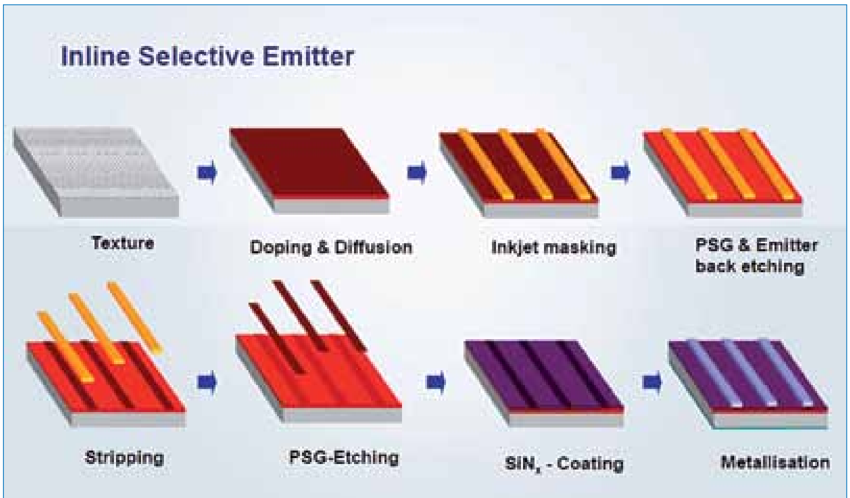

Figure 2. In-line selective emitter process steps (Schmid).

Firing

With such a broad range of primary changes being made to metallization geometries, there seems to be an increase in the risk of potential for physical damage through the contact. With over 90 customers in the industry, Despatch Industries' expertise in the sector led to its recent introduction of a transfer belt system for its 'Despatch UltraFlex' furnace, which it claims addresses this risk by contacting the cell only in the inactive area (the 1–1.5mm perimeter).

"The more specialized metallization geometries become, the more crucial the ability to tailor the thermal profile", noted Jeff Bell, Manager of Solar Product Management at Despatch Industries. "Even small temperature variations can affect aspect ratio and, as a result, current and shading. Our 'UltraFlex Microzone' technology enables very precise tailoring of the peak temperature and crucial 'time-above' profiles for new silver pastes."

The ability to change the thermal recipe along with the new materials and architectures is proving to be a necessity, and a feature that is fast attracting customer adoption of its technology, according to Bell.

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>
> -Jeff Bell, Despatch Industries

Another company that has been seeing increased activity for its next-generation metallization technology is BTU International, whose 'Tritan' metallization drying and firing system features a proprietary multi-speed drive system that enables aggressive temperature spikes without compromising the drying, burnout and cooling process steps.

Jan-Paul van Maaren, Ph.D., BTU International's Vice President of Marketing, noted: "The dual printing technology will still require the same firing technology as before but will probably require a more rapid spike… but we believe we are well ahead of customers' roadmaps, with the Titan capable of 200°C when temperatures of only 80 to 90°C are currently required."

BTU's Vice President of Sales, James Griffin, warned of some knock-on requirements related to the diffusion layer's becoming shallower and shallower.

"That dictates that the metallization step has less of a thermal budget to penetrate into the silicon. The contact has to be made, followed by a very quick 'freeze', because otherwise it will penetrate too deeply and create a short", noted Griffin.

He went on to say that some of BTU's customers were looking for totally alternative technologies to resolve the issue of printing and putting down narrow fingers. Evaluations using electroplating technologies are ongoing to achieve the next level of cell efficiencies. Griffin noted that BTU had technology available for that very application on the day we spoke.

Plating

Another company that is providing alternative technologies for metallization is Technic, Inc. According to Anthony Gallegos, Global Product Manager at the firm, many of the new entrants in cell manufacturing have shown great interest in moving to plating processes rather than following traditional metallization routes.

Technic offers 'Light-Induced Solar Plating' for front-side contacts. The company's light-induced electrodepostion is said to improve front-side conductivity while improving the overall uniformity. Utilizing its proprietary 'Technisol' chemistry, cell efficiency improvements of 0.4% are achievable.

However, Gallegos was quick to clarify that although some of the well-known cell efficiency leaders were known to be using electroplating methods with mixed results, these approaches used unconventional cell designs with the aim of achieving higher efficiencies. In contrast, the Technic ASL (alternative seed layer) process requires the use of conventional cell manufacturing methods in conjunction with Technic's process.

"The cell manufacturer can still utilize their existing manufacturing steps up to SiN_x", explained Gallegos. "Then they will laser grid lines into the SiN_x and use our ASL process to metallize the grid lines [chemical seed layer] followed by Light Induced Plating. Then the cells can be completed as normal."

Gallegos claimed that, as long as conventional cell designs are used, there are no problems with this plating technology, which is seen as offering a high-speed process ideal for volume production solar applications. Careful not to allude to customers' investigation of this plating alternative, Gallegos indicated that customer feedback and interest was increasing all the time. Perceived issues with contamination, bath life and waste treatment have all been dispensed with as the technology is widely used in other industries.

Conclusion

A path to 20% cell efficiencies using improvements focused on metallization processes while retaining low-cost manufacturing is well underway. Similarly, further enhancements to boost productivity and reduce material costs of selective emitter formation and double printing are ongoing. The ability to retain conventional processes with compatible in-line process step additions is providing the mainstream cell producers the ability to meet near-term manufacturing goals. How far such technologies can be pushed before more fundamental changes to cell designs, equipment and processes are required is not yet clear; however, the promise of 20% cell efficiencies with the lowest manufacturing costs will undoubtedly continue the growing adoption of photovoltaics technology.