SunDrive Copper Metallisation Demonstration Project

Knowledge Sharing Report – 2020/ARP006

Acknowledgments

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We would like to acknowledge the Gweagal people, the traditional custodians of the land upon which this project took place. We pay our respects to elders past, present, and emerging.

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Executive Summary

Current mainstream silicon photovoltaic (PV) technology is based on the passivated emitter and rear cell (PERC) design. As this solar cell technology fast approaches its efficiency limits, the industry is rapidly pursuing next generation passivated contact technology. One passivated contact technology that has attracted considerable interest worldwide is the silicon heterojunction (HJT) technology due to its >26% cell efficiencies on industrial wafers. However, a key concern for adoption of this technology is its high use of the precious metal silver for cell metallisation.

To address this key limiting cost and sustainability concern, SunDrive has developed a unique copper metallisation technology. Through reducing the metallisation cost whilst also retaining the high efficiency attributes of the silicon HJT technology, SunDrive's technology can significantly reduce the cost of PV generated electricity. By eliminating silver in the manufacturing process, the potential achievable manufacturing cost reduction can be up to 25% at the cell level and up to 17% at the module level, with further reductions in cost being achieved through higher module efficiencies (i.e., increased power generation per unit area).

The primary objective of this project was to demonstrate the manufacturability of SunDrive's copper electroplating technology applied to high efficiency silicon HJT solar cells using early-stage prototype production equipment. Specifically, the project aimed to:

1. Iterate on its cell design and processing to improve cell efficiency to 24-25%;
2. Scale its technology from individual industrial size cells to a commercial size module; and
3. Develop and demonstrate a small-scale prototype automated production line.

The outcomes of the project were:

1) Increased value delivered by silicon HJT solar cells with SunDrive's technology demonstrated by:
    - Improved cell design knowledge and understanding of cell characterisation and processing requirements leading to the achievement of a world record efficiency by SunDrive in 2021; and
    - Demonstrations of interconnection of copper-plated silicon HJT cells and of a small number of completed commercial size modules with SunDrive HJT cells for accelerated testing.
2) Increased skills, capacity and knowledge through the design, development and testing of small-scale prototype production equipment for high efficiency HJT cells capable of processing at a throughput of greater than 60 cells per hour with a yield exceeding 80%.
3) Initial commercialisation plans for SunDrive's plated-copper metallisation technology which has the potential to lower the production cost of next generation passivated contact silicon solar cells through elimination of silver for metallisation.
4) Improved TRL of SunDrive's copper metallisation technology from five to six.

Project Overview

Objectives

Current mainstream solar PV technology is fast approaching its efficiency limits. To meet the increasing energy demands for solar PV generational capacity, the global industry is rapidly pursuing next generation "passivated contact" technology, such as HJT solar cells. Whilst passivated contact technologies promise significant efficiency improvements over current cell technology, increased silver consumption in the metallisation step (the final step in converting a silicon wafer into a solar cell) presents growing cost and material sustainability challenges, which can limit the widespread adoption of this promising next generation solar PV.

The solar PV industry already represents 20% of global annual industrial silver consumption, with silver contributing up to half of the wafer-to-cell processing costs for passivated contact technology. Copper, a commodity metal, which is ~1000x more abundant and ~100x cheaper than silver, presents as the best alternative to ensure that PV can continue its rapid trajectory to multi-TW installed capacity by 2050. SunDrive has developed a novel copper plating technology that reduces the cost and increases the efficiency of silicon HJT technology.

The primary objective of this project was to demonstrate the manufacturability of SunDrive's copper electroplating technology applied to high efficiency silicon HJT solar cells using early-stage prototype production equipment. Specifically, the project aimed to:

1. Iterate its cell design and processing requirements to improve cell efficiency to 24-25% (which, if successful, would be amongst the world's most efficient industrial-size solar cells);
2. Scale its technology from individual industrial size cells to a commercial size module; and
3. Develop and demonstrate a small-scale prototype automated production line.

To complete this project, SunDrive established a number of industry collaborations with overseas world leading solar research institutions and companies. These collaborators provided the necessary non-metallised silicon HJT solar cell precursors for experimental use as well as assistance with in-depth solar cell characterization methods.

Technology Background

Introduction to SunDrive's Technology

SunDrive's unique copper metallisation process is depicted in Figure 1. Not only does the use of copper in the place of silver significantly reduce cost (the use of silver is the most expensive step in the solar cell production process), but it also provides a performance boost over existing silver screen-printing technologies. SunDrive's metallisation sequence comprises two key processes:

1. Low-cost, high-resolution patterning to achieve feature sizes comparable to laboratory-based lithography (<10 µm) but at a significantly lower material cost; and

2. An adhesion-enhancing direct copper plating process which provides high aspect ratio metal contacts that minimise shading and resistive losses, reducing material cost whilst boosting cell efficiency.

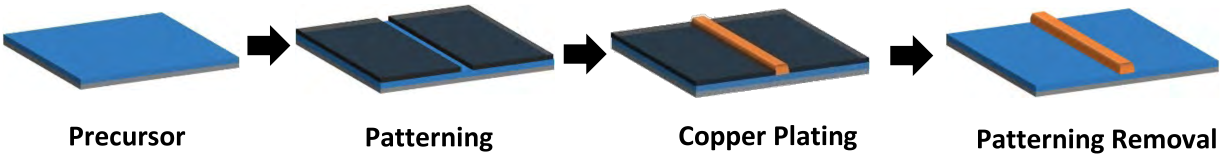

Figure 1: SunDrive's metallisation process.

Together, these two processes enable the direct replacement of the relatively wide (40-50 µm) silver fingers on a solar cell with narrow (10-15 µm) copper fingers (see Figure 2). This increases the amount of light that can be absorbed by a solar cell, resulting in an increased short circuit current and improved efficiency. When SunDrive's unique metallisation technology is applied to higher efficiency passivated contact cell technology (in particular, HJT solar cells), a further boost in efficiency can be obtained. In late 2021, SunDrive achieved a world record efficiency of 25.54% on a full area industrial wafer. Within a year of this result, SunDrive surpassed its own record to reach a top cell efficiency of 26.41%.

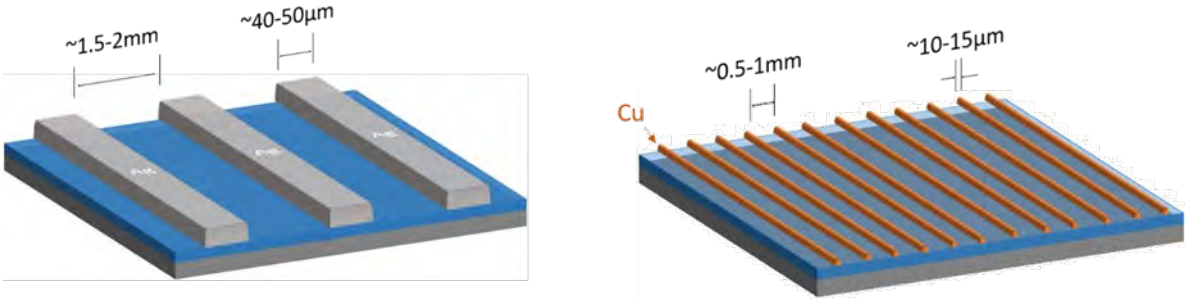

Figure 2: Comparison of the current silver-based metallisation technology (left) with SunDrive's copper-based metallisation (right).

Technical Challenges of Replacing Silver with Copper

The switch from silver to copper-based solar cell contacts may appear an obvious change to make to reduce both the cost of solar PV and the PV industry's dependence on silver. Indeed, several attempts have been made to achieve this transition in the past for the dominant p-type technology, which is based on the Passivated Emitter and Rear Cell (PERC) design. However, most approaches which have been trialled to date have either failed to be cost competitive or sufficiently durable.

As manufacturers begin to replace their PERC production lines with new higher efficiency passivated contact production lines, reducing silver usage has become even more important. Passivated contact cells typically require 2-3x more silver per Watt of solar cell power produced [1]. Consequently, the cost benefit that switching to copper can achieve is much greater for these cells. In addition, many of these cells cannot tolerate the high firing temperatures used for the screen-printed silver metallisation of PERC cells. This means low temperature silver pastes must be used and these pastes are more costly, more resistive and require long curing times.

However, despite the very clear incentives to replace silver with copper for next generation solar cells, technical challenges exist. First, it is very challenging to directly replace the silver in the screen-printed pastes with copper as the copper particles tend to oxidise. This causes the metal fingers to be very resistive and reduces cell efficiency. The oxidation of the copper particles can be prevented by capping the copper particles with silver. Whilst this approach can reduce silver usage, typically ~50% of the particle mass must comprise the silver coating [2] and this limits the cost effectiveness of the approach. Consequently, new methods of forming fingers and busbars on the cells will be required for an effective replacement of silver by copper.

Electroplating of copper has proven very successful for the formation of vias for printed circuit boards (PCBs) and interconnects in integrated circuits (ICs). Processes, equipment, and materials have been successfully developed for these industries and, to some extent, the PV industry can build upon the expertise and knowledge established for these industries. However, there are some key differences between the plating requirements for each of the PV, IC and PCB industries. First, the value of the plated products is very different. A plated silicon wafer with ICs can be worth more than 11,000 times that of a plated solar cell.[1] Second, whereas wafer throughputs over 1,000 wafers per hour are required for solar cell processing [3], throughputs of < 100 substrates per hour are typically targeted for IC and PCB copper electroplating. Finally, PCBs are rigid substrates of millimetre thickness and IC wafer thicknesses are increasing as wafer size increases for IC processes.[2] In contrast, silicon wafer thicknesses are reducing as wafer sizes are increasing, making wafer breakages, and reduced yield a much larger concern for PV applications. These large differences in product value, throughput and substrate properties mean that the equipment, processes, and materials used for copper plating for PV metallisation is likely to require new and innovative approaches.

The current focus of SunDrive's copper metallisation technology is its application to high efficiency HJT cells. Unlike PERC cells, where copper contacts are formed directly to the silicon cell through openings in a dielectric antireflection layer, for HJT cells the copper grid must be formed on a transparent conductive oxide (TCO). This means that the surface must be masked to prevent copper plating to the entire TCO surface. Masking and patterning of the mask are additional processes which can introduce extra cost and complexity when replacing silver metallisation with copper. Because of the high wafer throughputs required for solar cell processing, it is also difficult to use the lithography processes used in the semiconductor industry and thus alternative lower cost and faster processes are required. Several companies, SunDrive included, have demonstrated lower cost patterning processes that can be used to form cell metallisation masks for solar cell manufacturing. ***The key advantages offered by SunDrive's proprietary patterning process are its high resolution, adaptability to inline processing and low cost.***

Previous Commercialisation Attempts for Copper-based Metallisation

As mentioned above, there have been several attempts to replace the silver metallisation used by silicon solar cells with copper. BP Solar successfully introduced copper plating in the manufacturing of their laser-grooved buried grid Saturn cells in the early 2000's and, although

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[1] Each 300 mm semiconductor wafer can be used to produce ~ 600 A13 system-on-chip processors for Apple, each 98 mm^2 processor costing ~ US$30 (2020 prices). This corresponds to a wafer product value of US$18,000, compared to just ~ US$1.60 for a 22% efficiency PERC cell on a 210 mm wafer.

[2] As silicon wafers used for IC increase in diameter from 300 mm to 450 mm, the wafer thickness is expected to increase from 775 to 925 mm.

several BP Solar Saturn module installations continue to operate in the field, the metallisation process struggled to compete with screen printing of silver, partly due to its slow plating throughput [4]. Then, in 2009-2012 Suntech attempted to commercialise copper plating for their laser doped cells under the Pluto brand [5]. Unlike BP Solar's earlier electroless plating technology, Suntech pioneered the use of light-induced plating, a process whereby the solar cell is used to generate the electrical current for copper electrodeposition. Despite promising cell efficiencies and modules passing all the required IEC tests, the narrow Pluto fingers did not adhere strongly to the relatively smooth laser doped regions on the surface of the solar cell. After several years trying to address this problem, Suntech discontinued production of Pluto cells and focused on screen printed silver metallisation for their production.

Since Suntech's Pluto pilot production, several other companies have also attempted to introduce copper-based metallisation. Jinko, in partnership with German wet chemical equipment company Rena, demonstrated pilot production of copper plated metal-catalysed textured multi-crystalline cells [6]. However, despite the textured surfaces providing a rough surface for strong metal adhesion, the efficiency of the plated cells was lower than comparative screen-printed cells, presumably due to the plated copper penetrating through the diffused emitter.[3] ***This result by Jinko and Rena highlighted a key challenge for copper plating of PERC cells. When copper is plated directly to the silicon surface it requires a rough surface for sufficient adhesion; however, all demonstrated methods of introducing the required roughness for sufficient adhesion impact cell efficiency***.

A key difference between passivated contact and PERC cells is that, with passivated contact cells, the silicon surface remains covered with a passivating layer or stack of layers. ***This means that a copper plated grid can be introduced without any loss of efficiency***. For silicon HJT cells, the copper fingers and busbar are displaced from the silicon absorber (wafer) by both the amorphous silicon layers and the TCO. These layers act together to provide a barrier to copper entering the cell, providing the opportunity to form an adhesive cell interface for the plated copper without impacting the cell performance. ***An important feature of SunDrive's proprietary technology is the ability to form a copper grid that adheres strongly to the TCO surface***.

SunDrive's Technology Differentiation

As mentioned above, SunDrive's technology includes high resolution patterning and adhesive copper plating to TCOs. These technology differentiators are discussed in more detail below.

High Resolution Patterning

SunDrive's high resolution patterning process is an innovation involving material optimisation, equipment design and processing know-how. It makes possible the formation of copper plated fingers with a width of less than 10 µm uniformly across an industrial sized wafer. Figure 3 shows an optical photograph of a plated finger of width < 10 µm, which is difficult to achieve with other metallisation schemes. This high-resolution patterning has enabled SunDrive to achieve world

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[3] With metal-catalysed texturing, it can be difficult to form a uniform emitter across the entire surface due to the nanoscale roughness of the surface. Some regions across the surface can have a very shallow junction and, if copper diffuses close to the junction, undesirable electrical carrier recombination can occur.

record efficiencies on HJT precursor cells. Narrower fingers can reduce the area of the cell, which is shaded by the metallisation and, in doing so, increases the current generated by the cell. It also allows the fingers to be spaced more closely to each other, thereby reducing lateral resistance losses in the TCO of the solar cell. In comparison, most other patterning methods applied to the metallisation of silicon HJT cells result in finger widths of more than 20 µm [7-9] (see Figure 3).

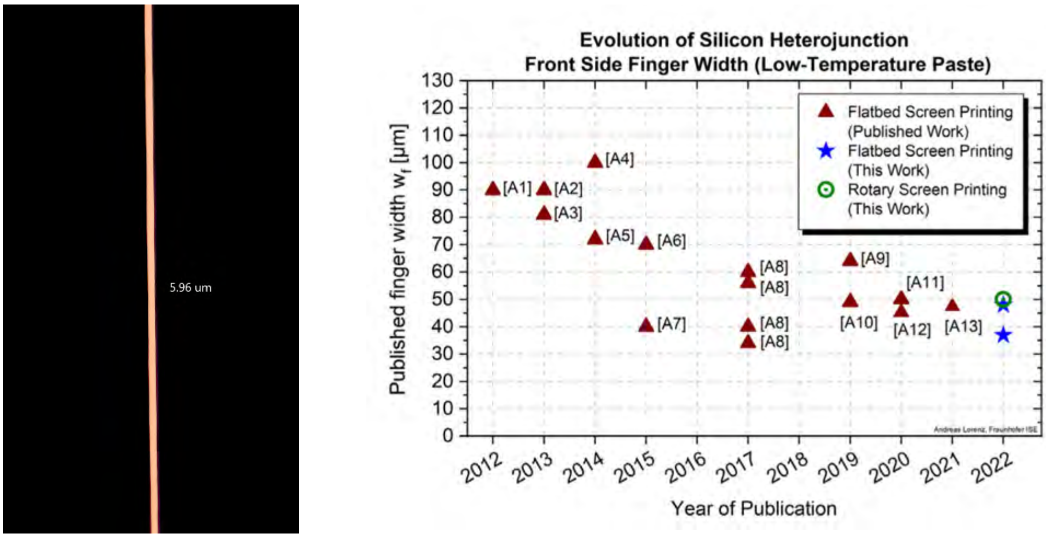

Figure 3: (Left) Optical micrograph of a SunDrive plated copper finger with a width <10 µm. (Right) Overview of the trends in screen-printed finger widths achieved on silicon HJT cells with low-temperature pastes (for details of the individual references see Lorenz et al. 2022 [10]).

Adhesive copper plating to TCOs

SunDrive has developed its own proprietary copper plating methods which ensure that the plated copper grid (comprising busbars and fingers) can be formed very rapidly and adhere strongly to the surface of the TCO of HJT solar cells. Achieving strong adhesion between a metal grid and the TCO surface can be challenging, and most other copper plating methods for HJT cells require that an additional metal seed layer be deposited via physical vapor deposition (PVD) techniques over the entire TCO surface before patterning in order to obtain sufficient interfacial adhesion. These approaches, which are generally referred to as 'etch-back' methods require, in addition to the cost of depositing the seed layer, an additional post-plating process to remove the seed layer over the cell areas not covered by the plated metal. This seed layer removal process can impact cell performance, making it more difficult to attain the high cell efficiencies which SunDrive has achieved.

SunDrive's adhesive copper plating process relies on a two-step plating process, whereby the process is 'tuned' for high interfacial adhesion using accurate measurements of finger adhesion.[4] To our knowledge, no other research group or company has the know-how and tools to perform these measurements and tune the process in the same way. SunDrive's technology is also

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[4] Measurements of finger adhesion have been shown to more accurately reflect interfacial adhesion than the more commonly used busbar pull tests [B. Phua, *Plated Metallisation for Silicon Solar Cells: A Deeper Dive into the Importance of Contact Adhesion*, UNSW PhD Thesis, 2022].

particularly advantageous in respect to adapting the metallisation process to new TCOs, which may provide performance and/or sustainability (e.g., low indium) benefits in the future.

SunDrive's proprietary metallisation process also allows the tuning of the finger shape to maximise light capture by the solar cell. If fingers can be engineered to be very reflective and shaped appropriately, a significant fraction of the incident light which encounters the fingers can be re-directed into the solar cell to generate photocurrent. This feature, along with SunDrive's high resolution patterning, has contributed to SunDrive's high cell efficiencies.

SunDrive is also addressing the challenge of processing throughput. As mentioned in **Technical Challenges of Replacing Silver with Copper**, much faster wafer processing throughputs are required for the PV industry than the IC and PCB industries, where wafers throughputs of < 100 per hour can be tolerated. SunDrive addresses this challenge through innovations in equipment, chemistry and know-how that allow plating rates which are more than twice that used in other industries without compromising on plated line resistance. This is a key achievement which differentiates SunDrive from all previous attempts to use copper plating in place of silver screen printing in the PV industry.

Applicability to Module Manufacturing

SunDrive has demonstrated the ability to interconnect their plated cells into modules using existing module fabrication processes.[5] Plated metallisation is well suited to thinner wafers which the industry is moving towards in order to reduce material usage [3]. This can correspond to more durable modules as fewer microcracks are introduced during the cell metallisation step. SunDrive's adhesive metallisation process can allow for both standard soldered interconnection methods and more recently developed lower temperature and busbar free processes where bonding between the cell metallisation and interconnection ribbons occurs during lamination. SunDrive's modules can also exploit their highly reflective cell metallisation. Light which falls on the fingers is reflected back into the cell from the front glass resulting in a cell-to-module gain in efficiency.

Another key advantage of SunDrive's technology is its high bifaciality. Bifacial modules are beneficial because they can also harvest light for power generation from the rear side of the modules. Rear side irradiation is determined by the albedo, which refers to the diffuse reflection from the ground surface and supporting fixtures around a mounted solar PV module. In some environments, this can be 20-30% of the incident irradiation on the module's front surface. Most current modules can only achieve a bifaciality of between 60-70%, meaning the conversion efficiency of light to electricity from the rear side is only 60-70% of the conversion efficiency of the front side. However, SunDrive's current silicon HJT cells have a bifaciality of ~90%, making SunDrive's modules much more efficient at harvesting light which can enter from the rear surface. This additional generation from the rear surface of modules can result in a lower levelized cost of electricity (LCOE) for utility-scale PV applications.

SunDrive's modules can also retain a larger fraction of their nameplate efficiency at high temperatures because of their low temperature coefficients of -0.23-0.25%/°C [14, 15]. The higher the open circuit voltage of a solar cell, the less degradation in efficiency that will occur as the ambient temperature increases. Typical bifacial PERC modules have a temperature

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[5] https://www.aumanufacturing.com.au/sundrive-fabricates-first-ever-full-size-solar-panel

coefficient of ~ -0.35 %/°C [16]. *So, in summary, under Australian conditions, SunDrive modules can generate more electricity than PERC modules due to their higher efficiency, high bifaciality and lower temperature coefficient. This higher yield (kWh/yr) further reduces the LCOE.*

Viability of Hi-Tech Manufacturing in Australia

SunDrive's technology addresses many of the perceived barriers to solar PV manufacturing in Australia. Historically, solar PV manufacturing costs were largely dominated by labour, land, and equipment capital. However, with the rapid learning which has occurred in automation and manufacturing equipment design over the past decade, costs are now largely dominated by more fundamental limitations: raw materials (namely silver and silicon), electricity and transportation (particularly when purchasing imported modules, primarily due to the weight of the module glass and aluminium). *SunDrive aims to address all three limitations by:*

1. *Utilising innovative technology to save on material costs (via eliminating silver and reducing silicon usage by using thinner wafers).*
2. *Using low-cost clean electricity in manufacturing (it is becoming more important for heavy industries and manufacturing, including solar PV manufacturing, to decarbonise as the world transitions to net zero).*
3. *Utilising efficiency enhancements and local module manufacturing to lower $/W transportation costs.*

The metallisation process being developed at SunDrive is innovative on the world stage. No PV manufacturer has achieved the patterning and copper metallisation quality and performance potential that has been achieved by SunDrive. To be able to demonstrate this process in manufacturing in Australia, a country which has no post 2010 experience in solar cell manufacturing despite a stellar history in PV research, offers the opportunity to kick-start a wave of advanced solar manufacturing growth in Australia.

The benefits to Australia provided by companies like SunDrive being successful in hi-tech manufacturing in Australia are substantial. Some key benefits are highlighted below.

1. Establishing solar PV manufacturing can provide Australia with world-class clean technology to support energy supply security. The recent war in Ukraine has highlighted the risk of countries relying too heavily on international partners for energy supply.
2. Due to its excellent solar energy resource, Australia has the potential to totally decarbonise its electricity supply using low-cost PV and wind, allowing its mining and refining industries to decarbonise and begin producing and exporting competitive low embodied emissions products.
3. Australia has all the material resources required to manufacture clean energy technology, including PV modules. Hence, developing and sustaining emerging clean energy companies, like SunDrive, can support strong resource industries and create employment opportunities for many Australians.
4. Finally, Australia has already invested heavily in PV knowledge and expertise at a research level. By supporting companies like SunDrive, which seek to build upon this investment, Australia can remain a leader in this critical energy technology field in the future.

With the right policy settings, Australia has the potential to become a solar manufacturing powerhouse. Australia has the greatest opportunity of any country to export its solar *resource – it is the sunniest continent with an extremely large land mass and very low population density. It can provide this export either (i) directly via long distance transmission lines (e.g., SunCable) or (ii) indirectly via the production of green hydrogen or green materials such green aluminium and green steel. By establishing local solar manufacturing capabilities, this will provide greater clean energy supply chain certainty to pursue such a grand solar vision as the world transitions to a decarbonised economy.*

Market Analysis

Global Heterojunction Market

Current mainstream silicon PV technology is based on the PERC solar cell design. As this technology fast approaches its efficiency limits, the global industry is rapidly pursuing next generation passivated contact technology. This higher efficiency silicon PV technology comprises tunnel oxide passivated contact (TOPCon) and HJT solar cell technologies. The established Chinese PV manufacturers are already quickly building capacity in one or both of these technologies. This is evidenced by the fact that several companies have commissioned or announced plans for GW-scale manufacturing (including a 4.8 GW contract for HJT equipment by India's Reliance RIL in 2022), and over 80 GW of expressions of interest in HJT manufacturing capacity in the past two years alone. The introduction of favourable policy incentives for domestic PV manufacturing outside of China has also seen a significant increase in the demand for high-efficiency silicon HJT manufacturing capacity around the world.

The most efficient silicon solar cells have been obtained using HJT technology. In 2017, Kaneka reported a designated area (i.e. edge effects neglected) efficiency of 26.7% on a silicon HJT back contacted lab-based cell [17]. This achievement has been followed by a series of rapid improvements in the efficiency of both-sides contacted cells fabricated on industrial silicon wafers by a number of companies, including SunDrive and Longi who are the only two companies to have achieved over 26% efficiency on full area (i.e., with solar cell edges included). These achievements have highlighted to the industry the very significant benefits that HJT cell technology can offer in reducing cost per Watt.

The latest International Technology Roadmap on PV (ITRPV) report projects that silicon HJT technology will grow in market share from ~ 5% in 2022 to ~ 20% by 2032 (see Figure 4). This prediction has consistently increased across successful ITRPV reports over the past 3 years. Market expansion beyond this decade is expected to accelerate even further with improvements being made in cell efficiency, manufacturing equipment and cost reductions. ***The global HJT cell market value was estimated at US $2.19 billion in 2022 and is projected to reach US $16.3 billion by 2028.***[6] ***This represents a CAGR of ~49.4% over this period, which is far larger than the 13.3% expected for the crystalline silicon PV market in general.***[7] It should be noted that these predictions for the growth in silicon HJT technology market share do not take into account the further market growth which SunDrive's high efficiencies using lower cost copper can stimulate.

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[6] https://www.marketwatch.com/press-release/hit-heterojunction-solar-cell-market-global-and-regional-analysis-and-forecast-2028-2023-01-10

[7] https://www.globenewswire.com/en/news-release/2021/09/02/2291062/0/en/Global-Crystalline-Silicon-Solar-PV-Market-is-Projected-to-Grow-at-a-CAGR-of-13-3-By-2031-Visiongain-Research-Inc.html

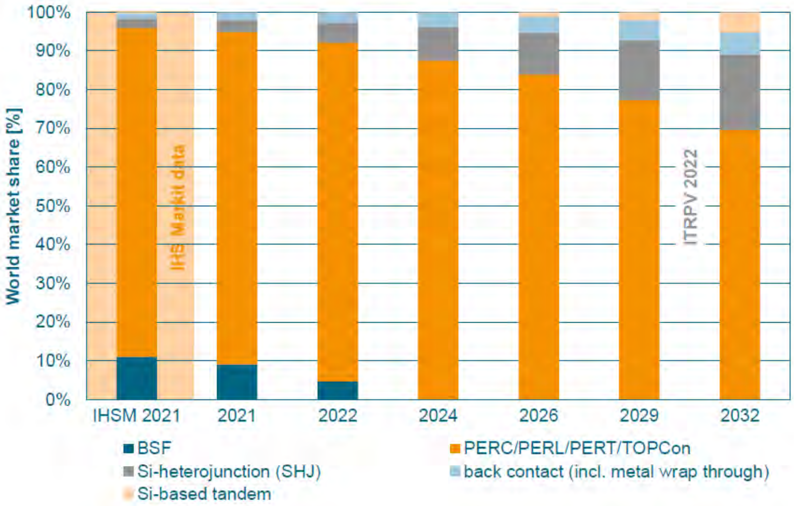

Figure 4: Predicted market share of different silicon solar cell technologies over the next decade (ITRPV, 2022).

Benefits of Heterojunction Technology

As module efficiency is increased, areal system costs per Watt of power generated are reduced due to increased power generation. Higher module efficiency also means that an average rooftop can generate more electricity (kWh) each day. The higher power generation from rooftop modules can avoid increased emissions from fossil fuel generators, a factor which will become increasingly important as more businesses and households use their rooftop generation to recharge electric vehicles. The proportion of electric vehicles on the road in Australia is expected to increase to 90% by 2050.[8] Consequently, the ability to recharge vehicles from higher capacity rooftop solar PV systems has the potential to reduce the need to commission as many public charging stations.

In addition to higher efficiency, silicon HJT technology can also provide:

- Higher bifacial performance (over 90% compared to 60-70% for PERC);
- Superior performance at higher temperatures (lower temperature coefficients); and
- Lower degradation rates (light-induced degradation – LID, potential-induced degradation – PID).

The performance and durability benefits of silicon HJT technologies directly contribute to lowering LCOE, which is a factor of great importance to the performance of utility-scale solar farms, especially when they are located in very hot areas such as in inland Australia (see **also Applicability to Module Manufacturing** and **Benefit of SunDrive's Technology to Australia**).

Impact of SunDrive's Technology

SunDrive's technology directly addresses the key challenge of high silver usage of current silicon HJT technology and, by doing so, it can further accelerate the adoption of the technology in manufacturing. Silicon HJT technology can provide a path to higher cell and module efficiencies, which can reduce the effective balance of system (BOS) costs for installations and hence LCOE. Additionally, almost all the reported perovskite-silicon tandem cells, which have a power

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[8] https://lighthouse.mq.edu.au/article/april-2022/whats-stopping-australians-from-buying-electric-cars

conversion efficiency (PCE) exceeding 25%, have used a HJT bottom cell (see Figure 5). This suggests that silicon HJT technology can play a critical enabling role in reducing the cost of PV generated electricity by making possible significantly higher efficiencies than any other contending current cell technology, either via a single junction PV device or as the bottom cell of a multijunction or tandem device. SunDrive's metallisation technology can also be applied to multijunction or tandem solar cells. Consequently, the value of SunDrive's technology extends beyond current generation single junction cells and modules.

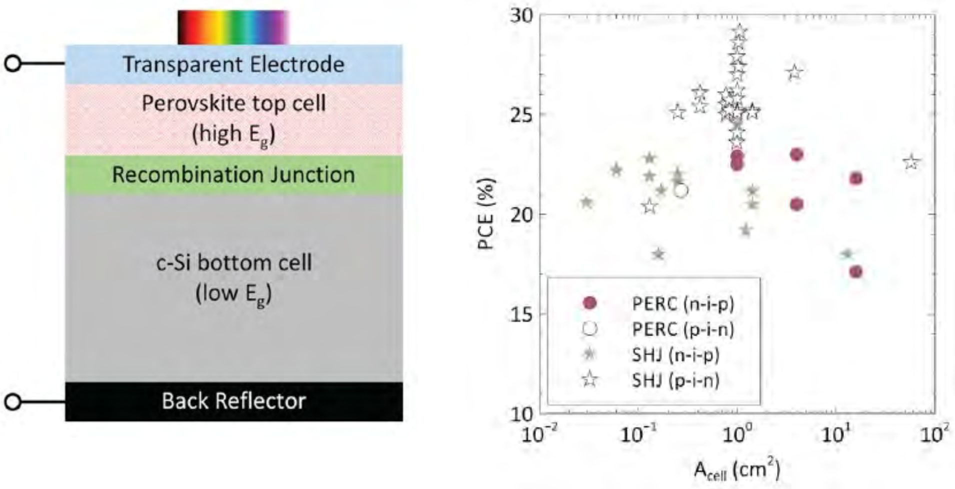

Figure 5: (left) Schematic of a perovskite-silicon tandem solar cell; and (right) power conversion efficiency (PCE) of reported perovskite-silicon tandem cells in terms of the polarity and bottom cell technology (from [18]).

SunDrive's successful replacement of silver with copper on highly efficient cells can also encourage more PV manufacturers to adopt the use of copper metallisation. This will stimulate additional investment in equipment and materials which can further reduce costs and increase LCOE benefits to users of electricity worldwide. Importantly, spreading adoption of copper-based metallisation in place of silver in PV can: (i) reduce the PV industry's demand for silver, allowing the use of silver to be reserved for critical industries where no clear alternatives exist; and (ii) reduce the embodied energy of PV modules worldwide.

Benefit of SunDrive's Technology to Australia

SunDrive's successful deployment of high efficiency PV modules with copper-based cell metallisation can result in more affordable high efficiency rooftop PV systems and can lower the LCOE of HJT technology for utility scale installations. There are numerous cost benefits of SunDrive's technology, which are discussed in more detail in **3. Cost Advantages of SunDrive's plated-copper metallisation technology**, however there are also technological benefits of both silicon HJT and SunDrive's metallisation technology to Australia.

Australia is a largely suburban country and has the highest penetration of residential rooftop solar in the world. For this reason, efficiency is important as it means that rooftops can generate more power. As more power is generated by rooftops, the demand on the central grid can be lessened. Higher rooftop generation will be especially important with the greater adoption of electric vehicles (as discussed in **Benefits of Heterojunction Technology**), as it will allow more home vehicle charging and reduce the demand for public charging stations. Silicon HJT technology provides the most plausible path to higher efficiency in commercially produced modules. The recent world record efficiencies for single junction cells have all been obtained using HJT technology on industrial wafers and almost all perovskite-silicon tandem cells that have achieved more than 25% efficiency have been achieved using HJT technology as the bottom cell. Application of SunDrive's high performance metallisation to HJT technology can push these limits even further to produce the most efficient commercial modules available worldwide.

Silicon HJT technology is also well suited to Australia's utility scale deployment. Most Australian solar farms are located in the hotter and more arid regions of the country because of the lower land value. Because of the lower temperature coefficient of HJT modules compared to current PERC modules, the power generation of HJT modules will not degrade as much in higher temperatures.

The fact that both silicon HJT cell technology and SunDrive's metallisation process are highly compatible with tandem cell manufacturing (for even higher efficiencies) can also be beneficial for Australia. If Australia establishes local silicon HJT cell expertise and manufacturing, it places the country in a good position to be a world leader also in tandem PV modules. Perovskite processing (as one example of a top cell) requires new industrial processes to be developed and, if Australia is an early player in this new solar PV technology, then it will have an established solar PV industry for many years to come.

Project Outcomes

SunDrive achieved all the proposed outcomes of this project. These outcomes are listed below with explanations of how each outcome was achieved.

1. Increased value delivered by HJT solar cells

(a) Improved cell design knowledge and understanding of cell characterisation and processing requirements to increasing cell efficiency

Over the course of this project, SunDrive extensively expanded its cell characterisation and modelling capabilities to further understand the potential of both electroplated contacts and the silicon HJT cell structure. To better understand the efficiency limitations of SunDrive's grid design, as well as exploit the uniquely narrow potential of plated contacts, resistive loss models were developed in-house from first principles to analyse areas of efficiency and fill factor (*FF*) improvements. These models articulated various loss mechanisms of the front and rear grid designs, including shading from fingers and busbars, contact resistance losses between the metal and transparent conductive oxide (TCO) and bulk resistive losses within the front metal grids. This model was used to evaluate grid design improvements for SunDrive's plated grid design to maximise current generation and minimise resistive losses in its cells, resulting in up to 0.6%$_{\text{abs}}$ efficiency boost purely from grid optimisation.

Access to new tools for characterisation throughout the project enabled detailed analysis of SunDrive's plating technology, helping to validate modelling and simulation results. These include, for example, photoluminescence imaging, which have enabled identification of defects, potential degradation and systematic processing pitfalls within SunDrive's wafers and cells. The use of surface profilers, in combination with scanning electron microscopy and transmission electron microscopy, allowed for clear confirmation of both the quality and geometry of our plated contacts, which facilitated improved understanding of plating performance and reliability. Examples of these techniques are highlighted in Figure 6.

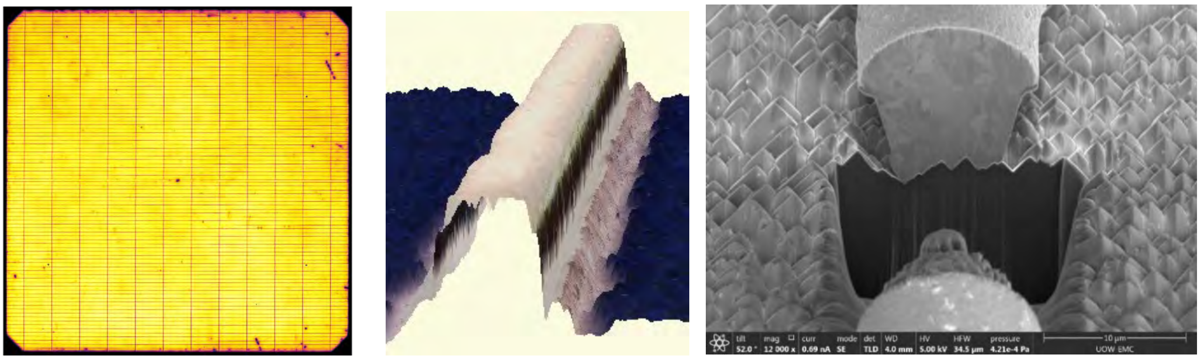

Figure 6: (left) Photoluminescence image of a 25.33% efficient copper-plated solar cell and corresponding surface profile of a copper finger (middle) and SEM image (right) of a selected finger located on the cell.

Over the course of the project, SunDrive's improvement in cell processing has led to the production of several world leading cell efficiencies. The implementation of new metallisation pattern designs identified using our grid optimization model led to substantially reduced shading and resistive losses. In combination, incorporation of a dual-layer anti-reflection coating enabled SunDrive to achieve short-circuit current densities exceeding 40 mA/cm^2, which are impressive for silicon HJT cells. Additionally, the use of in-house plating electrolyte formulations permitted the achievement of plated metallisation morphologies with enhanced aspect ratios of more than 0.7.

In September of 2021, SunDrive reported a world record efficiency for a commercial sized (total area of 274.5 cm^2) silicon HJT solar cell at 25.54%. The M6 cell precursor was fabricated by Maxwell Technologies. This result exceeded the 25.26% efficiency held by LONGi at the time by 0.28%$_{\text{abs}}$. Later in March of 2022, SunDrive increased its champion cell efficiency to 26.07% on a similar structure (M6 and bifacial). The increased efficiency was attributed to improvements in the optical coating deposited at SunDrive, further reductions in finger width from improvements in our masking process and optimisations in amorphous silicon crystallinity at Maxwell.

In August of 2022, Maxwell and SunDrive co-announced a 25.94% device fabricated on a low-indium TCO coated silicon heterojunction wafer. Indium is recognised as a longer-term unsustainable resource within the PV industry, especially as global PV production reaches TW scale. In this structure, a total indium reduction in the TCO film of up to 70% was achieved by adopting an improved magnetron sputtering method. Finally (for this project), in August of 2022, SunDrive announced a champion cell efficiency of 26.41% with further optimisations of its cell design and processing conditions.

The externally certified (at the Institute for Solar Energy Research in Hamelin (ISFH)) *I–V* characteristics for all the devices described above are shown in Figure 7. All solar cells were fabricated on industrially sized M6 wafers, with cell precursors provided by Maxwell. Figure 8 shows the progressive efficiency improvements that SunDrive has made during the two years of this project.

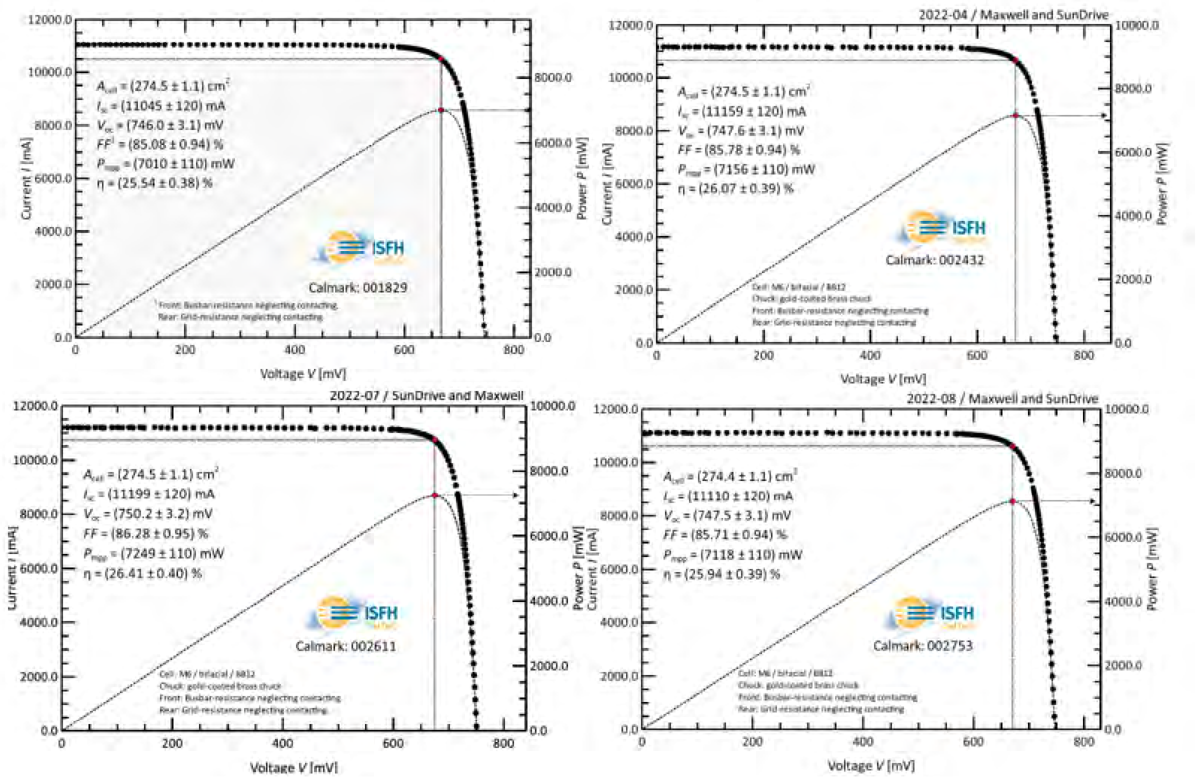

Figure 7: ISFH Certified current-voltage characteristics for SunDrive and Maxwell Technologies joint world record plated SHJ solar cell (top left), updated 26.07% device (top right), more recent 26.41% device (bottom left) and 25.94% low-indium TCO device (bottom right).

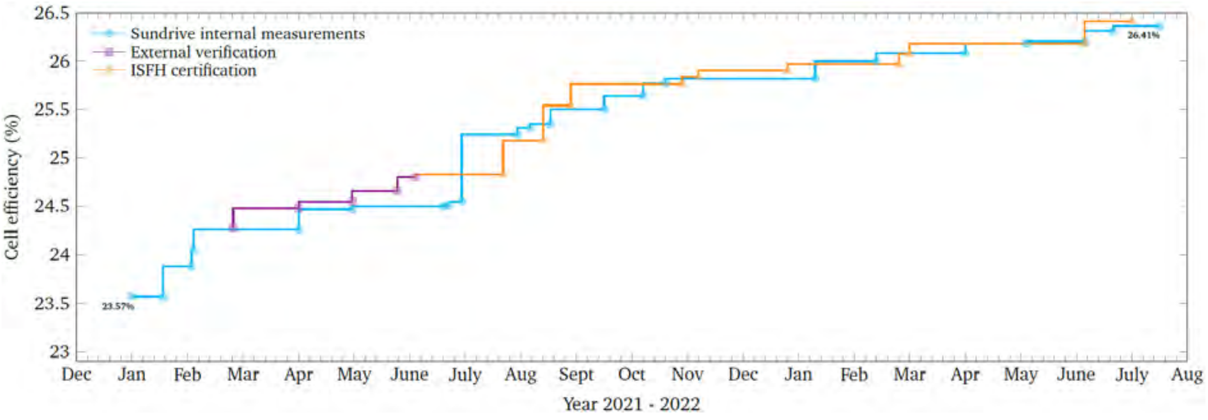

Figure 8: Improvements in cell efficiency achieved during this project.

(b) Development of interconnection methodologies and fabrication of a small number of completed commercial size modules with SunDrive HJT cells for accelerated testing

SunDrive's progression from cells to mini-modules and commercial size modules has been defined by several key steps. These steps have individually addressed the issues faced historically by other electroplated cell manufacturers, which have led to losses in long-term stability and structural reliability. The most problematic issues, which SunDrive addressed in this project, include solderability of plated copper during interconnection, interconnect wire and busbar adhesion, copper-diffusion-related degradation, encapsulant-copper reactivity, and copper oxidation.

Improving the solderability of copper plated contacts

Soldering to pure copper can be problematic due to: (i) poor wettability of the solder across the copper surface; and (ii) oxidation of the copper surface, which results in poor thermal conductivity leading to a poor solder interface. The PV industry has addressed these issues through the use of capping layers (tin, silver, etc) which provide enhanced wettability at the interface for solder and prevent copper oxidation. However, it remains necessary to ensure that the flux used for soldering allows for sufficient solder wetting of the capping layer surface at the contact pads of copper plated cells.

Throughout this project, SunDrive tested various forms of flux and soldering techniques to develop a soldering process which results in sufficient solder wetting of capped plated copper contact pads for strong adhesion of interconnect wires. The optical microscope images in Figure 9 depict both adequate wetting (left image) and inadequate wetting (right image) of solder on capped plated copper contact pads.

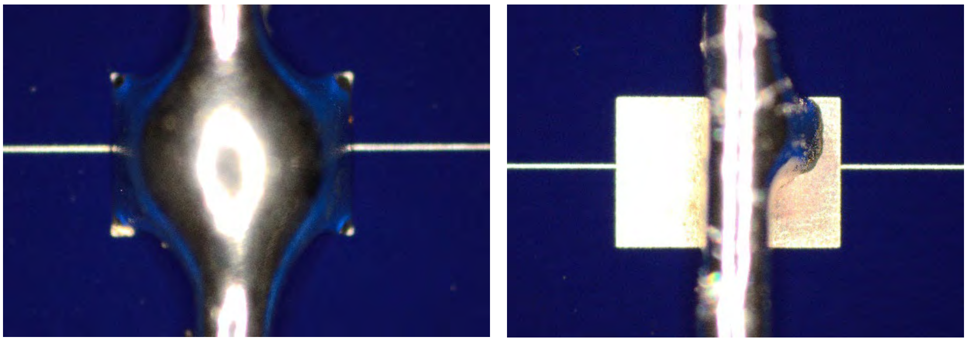

Figure 9: Optical microscope images of contact pad and wire interconnect with adequate solder spread and wetting (left) and inadequate wetting (right).

Enhancing the adhesion of plated contacts to HJT cells

Another frequently reported problem for copper-plated cells is the poor adhesion between the interconnection wire and copper-plated busbars. This project focussed on improving adhesion: (i) between the TCO and the plated copper; and also (ii) between the plated copper cell grid and the interconnecting ribbon/wires. Early attempts to introduce copper plating for silicon solar cells resulted in cells which were not able to be interconnected by soldering. This resulted in new and more costly methods of interconnection to be used. In this project, interconnection by soldering was considered a key requirement for SunDrive's metallisation to be commercially viable.

By optimising the plating electrolytes, anode materials and plating process, SunDrive was able to demonstrate soldering of copper plated contacts with very strong adhesion. The strength of the achieved adhesion is qualitatively demonstrated by images (see Figure 10) which show the removal of both TCO and underlying silicon during routine busbar pull testing. The fracturing and removal of shards from the underlying silicon wafer shown in Figure 10 indicates that the solder bond strength exceeds the sheer strength of the silicon itself. More recent testing of new busbar designs has further enhanced the soldering adhesion strength beyond what has been previously achieved in the industry. To our knowledge, adhesion at this strong level has never been achieved for silicon HJT cells, including HJT cells with screen-printed silver metallisation. Hence, SunDrive's developed proprietary metallisation process represents a significant PV industry achievement.

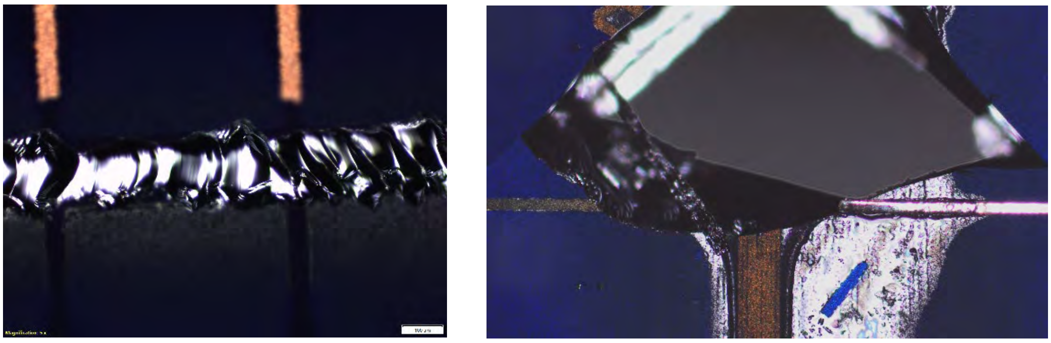

Figure 10: Optical microscope image of resulting underlying silicon and fracturing of a silicon wafer after the forced removal of interconnect ribbon from busbar during standard busbar reliability pull testing.

Minimising cell-to-module losses during module fabrication

Predictive models for module performance were developed utilizing *I-V* data measured from individual cells to evaluate cell-to-module (CTM) losses and gains. The developed models were used to predict the performance of modules, optimize stringing arrangements and simulate field events including partial shading. Through the use of CTM modelling, it was identified that the majority of the electrical losses in SunDrive's early-stage modules occurred at the reflective surfaces of the front module glass, parasitic adsorption in encapsulant materials and resistive losses in the junction boxes and cabling. The CTM analysis helped identify where improved materials should be sourced. An example of the CTM analysis generated in partnership with UNSW is depicted in Figure 11.

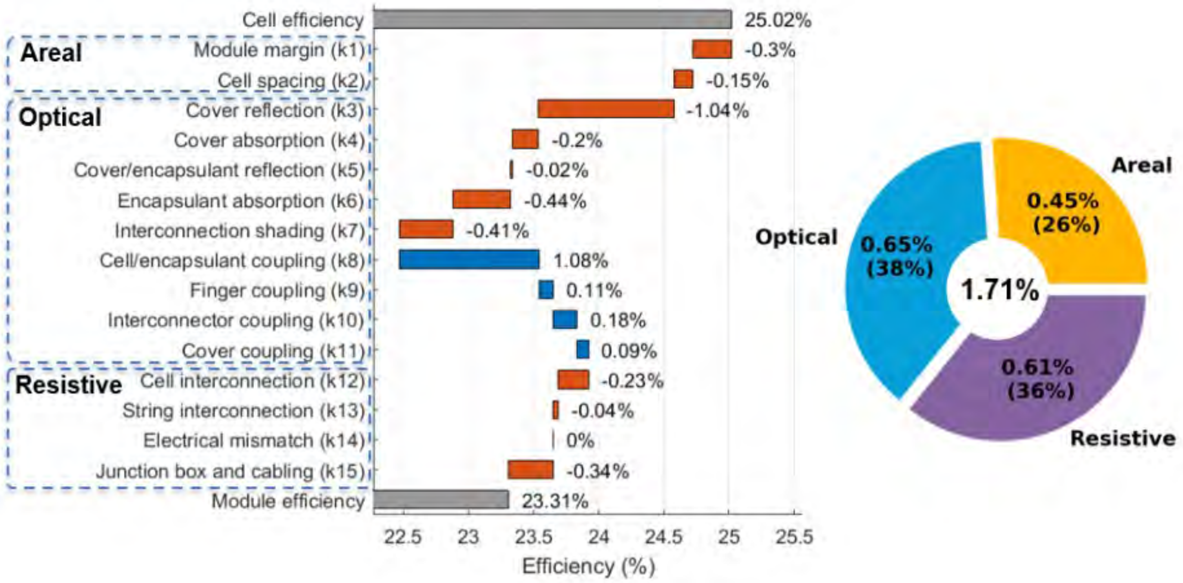

Figure 11: CTM analysis of SunDrive mini modules (2 x half-cut M6 cells) generated using the SmartCalc.CTM software.

For the CTM analysis shown in in Figure 11, full M6 cells were plated and then cleaved to half cells with an in-house laser process to produce two half cut M6 mini-modules. The cleaving step reduced the cell efficiency from 25.32% to a starting (half-cell) efficiency of 25.02% (absolute efficiency loss of 0.3%). Reducing cutting losses has been a key challenge for silicon HJT technology, with cutting losses being significantly higher than PERC cells. The industry's transition to M12 wafers and cutting these wafers into half before cell processing has addressed this key limitation for the commercialisation of silicon HJT technology as all the edges of the wafer remain coated and passivated.

Development of mini-modules and commercial sized modules for reliability testing:

As part of this project, SunDrive successfully demonstrated the integration of copper plated cells into commercial sized solar modules. A comparative silver-screen printed module was also fabricated using precursors from the same batch to evaluate potential advantages of copper plating over silver screen printing. Overall, a 0.67%$_{abs}$ boost in active-area module efficiency was observed for the copper-plated modules. This increase was attributed to an increase in: (i) I_{SC} (~0.2 A) due to narrower fingers; and (ii) FF (0.31%) due to more conductive fingers. The measured I-V parameters are illustrated in Figure 12 and Table 1.

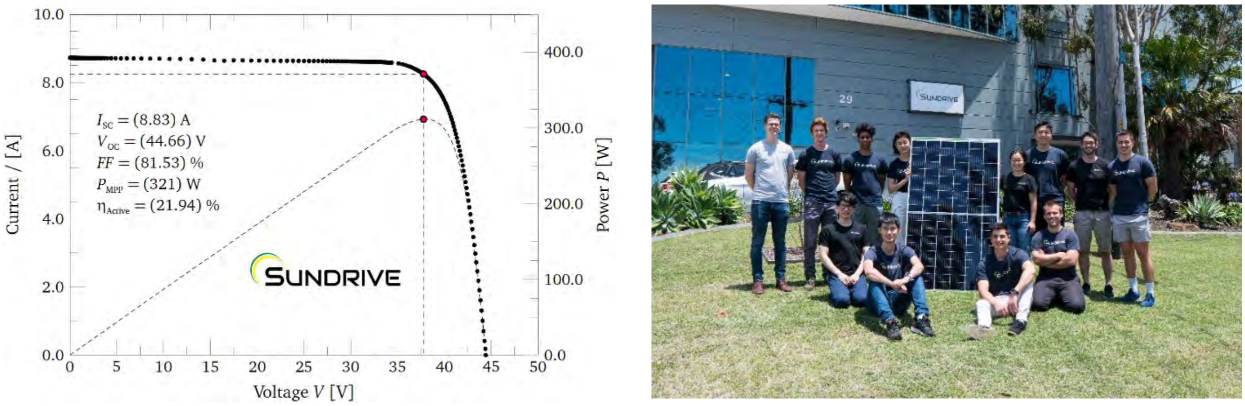

Figure 12: I-V curve and photograph of one of SunDrive's first Cu-plated commercial sized solar modules.

Table 1 IV parameters of SunDrive's first demonstration copper plated module and a comparative silver screen printed solar module. Both modules comprised 120 x M2 half-cells.

	V_{OC} (V)	I_{SC} (A)	FF (%)	P_{max} (W)	R_s (Ω)	Eff$_{Active}$ (%)
Copper plated module	44.66	8.83	81.53	321	0.33	21.94
Silver screen-printed module	44.46	8.63	81.22	312	0.34	21.27

During the project a large number of mini modules were fabricated for reliability testing of SunDrive's bill of materials. This reliability testing included light-induced degradation testing (>1000 hours); UV degradation testing; damp heat (up to 3000 hours or 3x IEC) and thermal cycling (600 cycles or 3x IEC). Environmental chamber testing enabled rapid evaluation of bulk module materials such as encapsulants and backsheets. For example, as seen in Figure 13 below, after 2000 hours of damp heat testing, SunDrive's glass-glass bifacial modules experienced minimal degradation. This result demonstrates that copper-plated silicon HJT modules can pass routine IEC testing, though clearly field testing will also be required to ultimately confirm durability of the modules in the field under different environmental conditions.

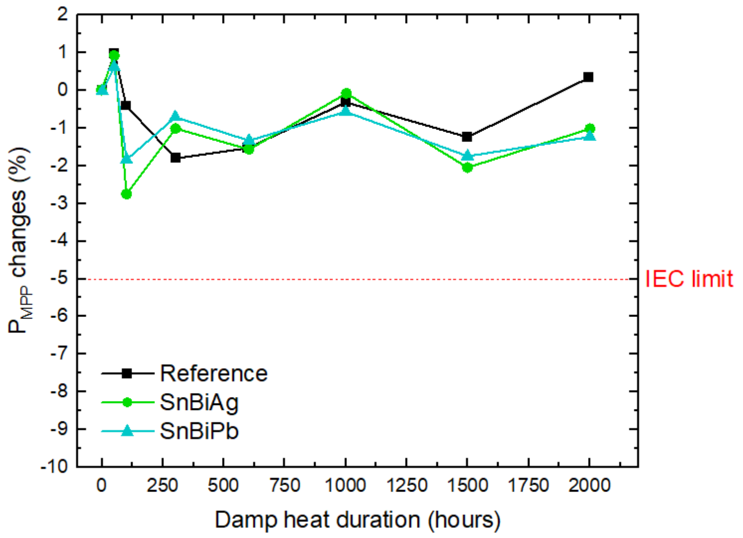

Figure 13: Power degradation of SunDrive glass-glass modules (with interconnection wires coated with both SnBiAg and SnBiPb (low temperature) solders) after 2000 of DH environmental testing.

2. Development and testing of small-scale automated prototype production equipment

During this project, SunDrive has increased skills, capacity and knowledge through the design, development and testing of automated prototype production equipment capable of producing high efficiency silicon HJT cells at a throughput of > 60 cells per hour and with a yield exceeding 80%. SunDrive's prototype cell metallisation production line can be divided into two main processing steps – patterning and plating.

Patterning Production Tool Development

SunDrive's patterning technology comprises of two key production tools: (i) a masking tool to form a protective coating in preparation for SunDrive's plating process (see Figure 1); and (ii) a patterning tool to create the selective openings for contact grid formation. SunDrive's lab-based masking process required a high degree of human input, from loading individual wafers, visual inspection of wafers and manual intervention for removal of mask defects. Several coating layer deposition methods were evaluated for the automated process with the objective of forming uniform masking layers with minimal defects. A vision camera system was implemented for alignment and quality control to maximise the output yield of coated cells from the deposition tool. Optimisation of SunDrive's masking process conditions and masking layer composition resulted in the processing time for the masking of M6 wafers being reduced by 97% compared to SunDrive's existing lab-based process.

Due to the rapid industry transition from M6 to M12 wafer sizes, it was necessary to upgrade the automated masking system to half-cut M12[9] solar cell precursors. With completion of this wafer size upgrade, continuous masking of 60 x half-cut M12 precursors per hour was achieved. This processing throughput corresponds to a production capacity of ~2.3 MW/yr assuming a half-cut

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[9] SunDrive's cell precursors were fabricated on M12 wafers which had been cut in halves before cell processing. These precursors are referred to as half-cut M12 throughout this report.

M12 cell power of 5.4 W, 80% production line yield, operating for an industrial standard duration of 22 hours per day for 330 days per year.

With higher precision machining to be implemented in future iterations of the tool, SunDrive is targeting a single-lane masking tool throughput of ~510 cells per hour, which is equivalent to ~20 MW/yr capacity (for an M12 half-cut cell with a power output of 5.4 W and 95% production line yield at standard industrial operating durations). To achieve higher throughputs beyond this point, SunDrive's masking tool would be scaled to multi-lane operation.

Complementary to SunDrive's masking process is the selective patterning of the mask to create openings for the copper plated metallisation (see Figure 1). Patterning is often an expensive industrial process requiring highly precise alignment. Robotic automation and proprietary methods of alignment were used to achieve a highly repeatable process without the need for high precision vision alignment systems. These improvements, along with innovations in masking materials, have enabled SunDrive to achieve finger widths as narrow as 6 µm [see Figure 14(right)]. Furthermore, these plated metal resolutions are up to 60% finer than what has been reported by competing processes being applied to silicon HJT cells.

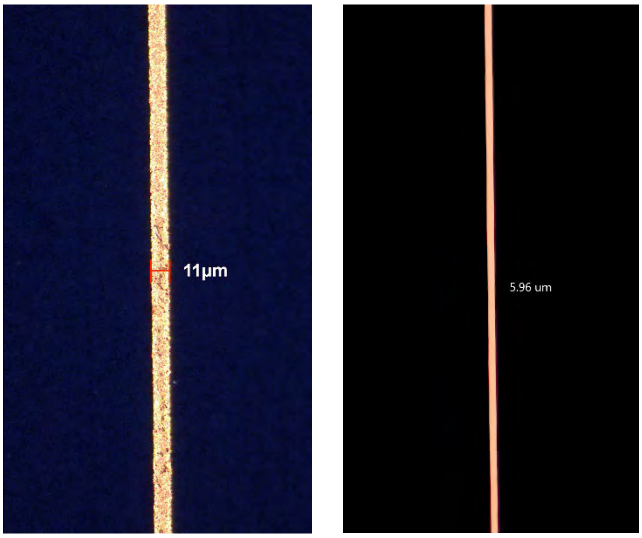

Figure 14: (left) Optical microscope image of 11 µm fingers on our previous 25.54% world record device and (right) <6 µm finger width capabilities from our improved mask patterning techniques.

To achieve the desired throughput for its prototype production-scale patterning equipment, the efficiency of its selective patterning approach was improved to achieve processing durations of more than 1 wafer per minute, whilst also increasing uniformity. The repeatability and yield of the masking and patterning steps can be summarized using several key metrics. Figure 15 shows that the thickness uniformity of the deposited masking layer across half-cut M12 cells (4.9 µm, σ = 0.32) using the prototype equipment was comparable to that achieved with the lab-scale tool.

Figure 15 (right) compares the consistency of the lab-based (M6) and prototype line (half-cut M12) finger opening widths measured on a batch of > 40 cells. Overall, SunDrive's M12 prototype line tool produces a finer finger resolution albeit with a slightly higher spread (9.4 µm, σ = 1.7) when compared to the lab-based M6 tools (9.9 µm, σ = 1.2). This demonstrates comparable results and thus, successful scaling of SunDrive's lab-based equipment and process towards a higher throughput M12 compatible production tool and process.

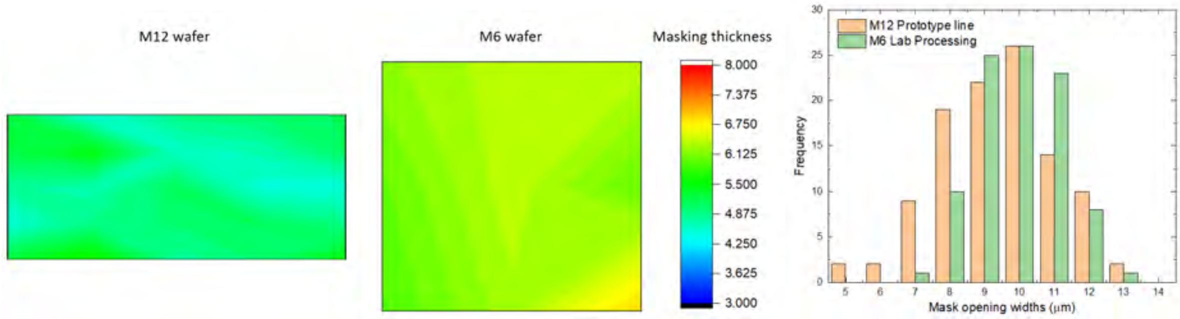

Figure 15: Masking layer thickness variation on randomly selected M12 wafer (left) and M6 wafer (centre) after masking deposition on prototype line and lab-based tool, respectively. Histogram plot of measured opening widths on M12 half-cut cells (n > 40) processed on prototype mask patterning tool and M6 cells processed on lab-based patterning tool (right).

Yield was evaluated for the entire patterning process (masking + patterning) on a 'pass/fail' analysis, whereby the qualification metrics for 'pass' conditions were opening uniformity and average width consistent with that mentioned above (average width ~9 µm, $\sigma < 2$). The results of SunDrive's yield analysis are shown in Figure 16.

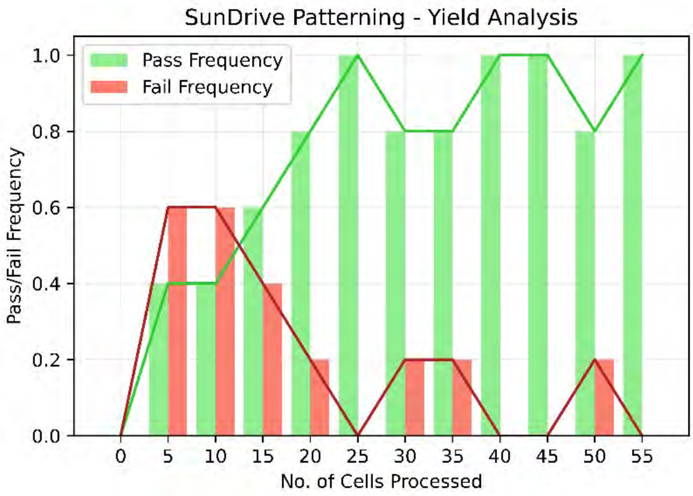

Figure 16: Yield analysis for SunDrive's patterning process (masking + patterning) on prototype patterning equipment designed for half-cut M12 precursor wafers (*n* = 54).

The optimised masking + patterning process achieved a performance yield of ~90% consistently across the last 30 precursors processed. This is comparable to SunDrive's lab-scale processing which involves extensive manual intervention at a significantly slower processing throughput. The remaining variance in the yield was primarily due to residual alignment/resolution losses from the use of lower quality machining parts in these early prototype tool iterations. SunDrive is currently upgrading the design of its masking and patterning tools with higher precision machining and automation to further minimise process variation and improve the overall yield of its production-scale patterning process.

Plating Production Tool Development

Automated cell handling and transport between different plating stages, including in-situ rinsing, were implemented to significantly increase throughput and also reduce yield loss from breakage. The implementation of improved agitation through recirculation of plating electrolyte during processing was also able to significantly increase plating rate to achieve higher throughput. The combination of improved automation of handling and wafer transfer between plating sub-steps with increased plating rates achievable with solution agitation during plating enabled equivalent throughputs comparable to those achieved with SunDrive's prototype patterning tools (equivalent to ~2 MW/yr for a standard half-cut M12 power output of 5.4 W and 80% production line yield).

Another key upgrade SunDrive adopted, when developing its prototype plating equipment, was to improve the plating chemistry to facilitate the faster plating rates achievable with the inclusion of electrolyte circulation. By reformulating the chemistry, SunDrive was not only able to achieve faster plating rates without detrimentally affecting plating quality but was also able to achieve superior aspect ratios (ratio of contact height to contact width) as well as contact morphologies that helped to increase cell efficiency. As can be seen in the images presented in Figure 17, high aspect ratios of 1 – 1.2 were obtained with the new copper chemistry (i.e., more vertical plating than lateral growth), compared with < 0.6 for the previously used chemistry.

The improved plating approach used by SunDrive's prototype plating equipment has also improved the finger smoothness and copper deposit quality, both factors contributing to increased cell efficiency. As can be seen in the SEM images in Figure 17, the surfaces of the contacts are significantly smoother with the new optimised SunDrive copper chemistry. In addition, the new chemistry resulted in fewer grain boundaries and defects. This improved plating quality reduces electron scattering and line resistance of the copper plated fingers. These improvements, combined with reduced shading losses due to narrower contacts, increase light capture from the smoother, rounder contact surface (advantage achieved in modules) and lower resistive losses due to low defect density copper electroplating. Overall, this has contributed to, on average, over 1.2% enhancement in *FF* and 0.8 mA/cm^2 improvement in J_{SC} over the last year of the project.

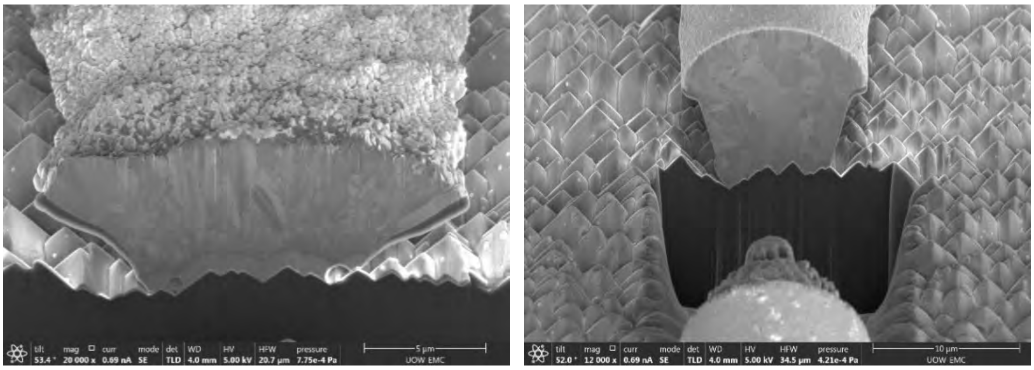

Figure 17: Comparison of SunDrive plating using (left) original laboratory plating process and (right) prototype production plating equipment.

An example of a half-cut M12 copper plated HJT cell fabricated with SunDrive's prototype production tool is shown in Figure 18. The plating quality can be seen to be similar for both the lab plating process [Figure 19 (left)] and prototype production equipment [Figure 19 (right)].

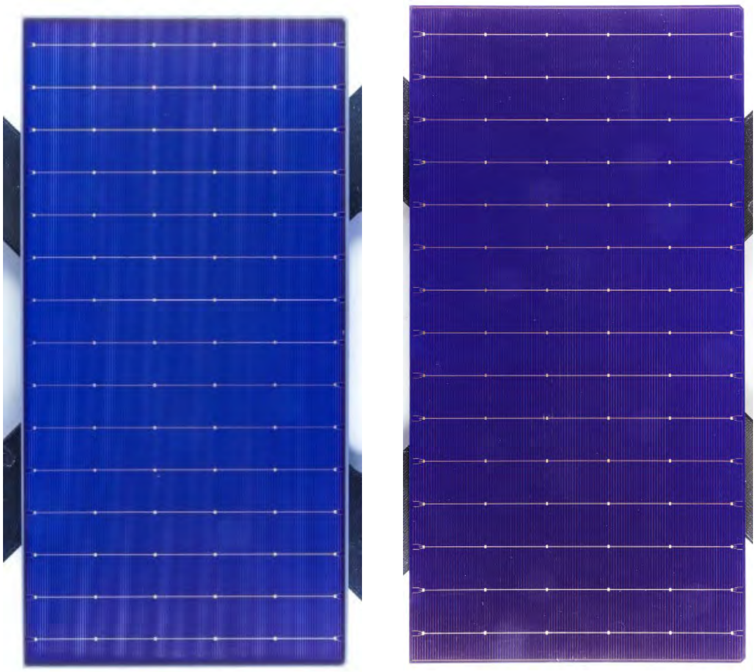

Figure 18: Photograph of SunDrive's rear side (left) and front side (right) plated half-cut M12 cell consisting of 15 busbars.

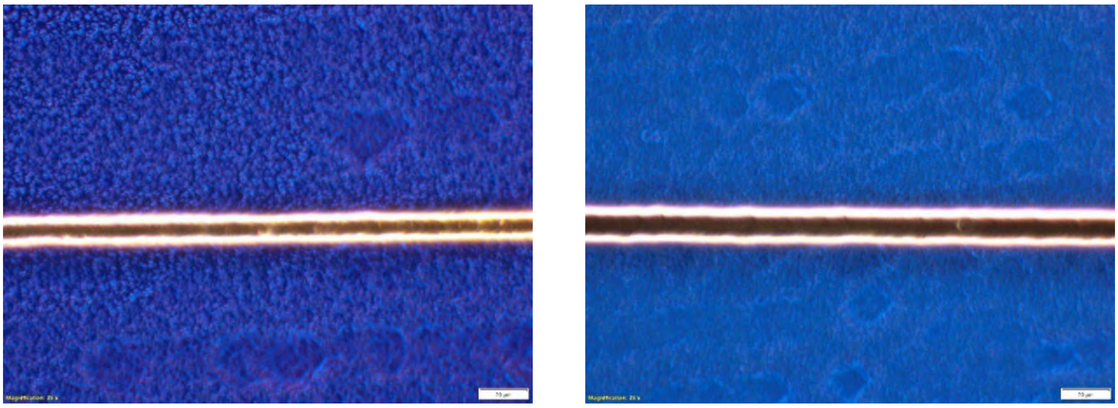

Figure 19: Optical microscope images of SunDrive copper-plated fingers using its lab equipment (left) and prototype production equipment (right). The fingers were 10.2 µm and 11.1 µm wide and 6.7 µm and 7.0 µm high, respectively.

SunDrive examined plating yield based on the cell's electrical performance as a metric of assessment. Overall, the prototype plating performance was within 0.5%$_{rel}$ of the lab process, demonstrating effective translation of the lab plating process to prototype production. Whilst both plating methods demonstrated yields over 80%, the repeatability of the prototype plating production tool was significantly improved over the lab process. The efficiency standard deviation was 27% lower for the prototype plating tool compared with the lab plating tool. This is in part due to two superior tool design features of the prototype plating tool, namely:

1) Removal of manual handling from the plating process with semi-automated wafer handling between stages; and
2) Controlled fluid flow across the cell surface during plating.

3. Cost Advantages of SunDrive's plated-copper metallisation technology

Commercialisation of copper metallisation technology has the potential to lower the production cost of next generation passivated contact silicon solar cells through elimination of silver for metallisation. Silver costs are as high as US 5c/W[10] for HJT solar cells. By eliminating silver, the potential achievable cost reduction can be up to 25% at the cell level[11] and up to 17% at the module level.[12] Coupled with the observed 0.4-0.5%$_{abs}$ efficiency boost also achievable with SunDrive's technology as identified in this project, the cost/W is reduced even further. The higher efficiency also corresponds to a reduction in the balance of systems cost. The 'value of efficiency' has been estimated at ~USD 20/m^2/% efficiency for residential rooftop systems and ~USD 8/m^2/% efficiency for utility scale systems [19].

SunDrive's technology can also reduce the LCOE for Australian electricity consumers. In addition to the lower module costs and reduced areal cost of systems, further benefits can be derived from both increased module bifaciality, and a reduced temperature coefficient as explained earlier in this report. These electricity yield benefits are more complex to quantify as the benefit depends on where modules are installed. Future analyses will be performed to provide LCOE estimates for different Australian regions and electricity yield comparisons with alternative technologies. Although other technologies (e.g., silicon tandems) can also provide a pathway to higher efficiency, SunDrive's technology has the important advantage that it can directly build upon existing cell (precursor) and module (interconnection) technologies which are already proven in the field.

Unlike most existing solar cell metallisation processes, SunDrive's copper metallisation can be applied to thinner wafers. This can result in both higher efficiencies and lower material costs in the future. N-type silicon wafers for HJT cells are expected to decrease from current wafer thicknesses of ~ 155 µm to 125 µm by 2032, whereas p-type wafer thickness will reduce from ~ 160 µm to stabilise at 140 µm over the same time frame. This reduced silicon usage will be reflected in a larger cost reduction over time for HJT cell technology compared to existing p-type technology, where wafer thinning is currently limited by the screen-printing process.

As the industry scales to TW manufacturing capacities, the transition to copper from silver becomes more critical. Exhaustion of silver reserves by unbounded silver use for PV manufacturing will act to further increase silver metal and paste costs and exacerbate the metallisation cost challenges. Since silicon HJT cells currently use 2-3 times the amount of silver per cell as PERC cells, the continued usage of screen-printed silver for these cells will ultimately limit their manufacturing capacity. By addressing this critical cost and sustainability constraint for silicon HJT technology, SunDrive can effectively provide a path to higher efficiency and lower electricity costs to consumers.

4. TRL of SunDrive's technology

The following key achievements of this project:

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[10] https://miworkshop.info/wp-content/uploads/2021/11/4.1_Lachowicz_CSEM.pdf

[11] Assuming HJT cell cost of US 20c/W

[12] Assuming HJT module cost of US 30c/W

1. Development of prototype production-compatible equipment for the individual steps in SunDrive's proprietary metallisation sequence
2. Demonstration of copper plated silicon HJT on industrial cell precursors; and
3. Demonstration of copper plated silicon HJT modules which can pass the key IEC reliability tests;

have increased the overall TRL of SunDrive's technology from 5 to 6.

Conclusions

This project has demonstrated the commercial feasibility of SunDrive's copper plated metallisation technology for silicon HJT cells and modules though achievement of all project outcomes.

A key highlight of this project has been the demonstration of a world record efficiency of 25.54% in September of 2021 on an industrial M6 wafer. This achievement was the result of improvements in cell design, knowledge and extensive use of cell characterisation to systematically address and mitigate electrical losses in copper plated HJT solar cells.

During the course of this project, SunDrive has also demonstrated the viability of their proprietary technology in modules. It was demonstrated that previous durability concerns regarding adhesion of plated copper could be addressed by ensuring strong interfacial adhesion of the plated copper to both the solar cell and to the solder of the interconnect wire. This important achievement allows SunDrive to use standard soldered solar cell interconnection in the fabrication of its modules. In addition, it was shown that glass-glass bifacial modules can pass up to 3 x the IEC requirements for damp heat and thermal cycling, as well as required tests for light stability.

Prototype production equipment was successfully developed for both the patterning and plating steps of SunDrive's proprietary process. Throughput and repeatability tests were conducted to ensure that cells could be metallised at a throughput of 60 cells per hour with a yield of at least 80%. Future production equipment refinements will aim to improve both throughput and yield.

Combined, these project achievements have resulted in the TRL of SunDrive's metallisation technology increasing from 5 to 6. In addition, this project has advanced knowledge and understanding in the following areas:

- Efficiency potential of silicon HJT solar cells;
- Suitability of low-cost mask patterning methods for large area substrates such as solar cells;
- Tuning of plating chemistry for improved contact formation;
- Formation of strongly adhesive plated contacts to the conductive layers of silicon HJT cells;
- Formation of strong solder bonds to plated copper contacts of solar cells;
- Durability of copper plated silicon HJT modules as assessed by IEC standard testing;
- Equipment designs for masking, patterning and the plating of metal grid structures.

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18. Razzaq, A., et al., *Silicon heterojunction solar cells: Techno-economic assessment and opportunities*. Joule, 2022. **6**(3): p. 514-542.
19. Peters, I.M., et al., *The Value of Efficiency in Photovoltaics*. Joule, 2019. **3**: p. 2732-2747.

Knowledge Sharing

Although many technological aspects of this project were not able to be published due to confidentiality, learning from the project was disseminated through invited presentations, podcasts and conference presentations. A list of these public disclosures is below.

Publications

T. Tang, Cao. Y, C. Peng, G. Dong, C. He, X. Ran, H. Jiang, V. Allen, X. Cao, J. Zhou, "Achievement of 25.54% power conversion efficiency by optimization of current losses at the front side of silicon heterojunction solar cells", Prog Photovolt Res Appl. 2022;1-12.doi:10.1002/pip.3641

Presentations

Asia Pacific Solar Research Conference

- A. Lennon, "The Ascent of Silicon Heterojunction Technology: Can the Technology be Sustainably Manufactured at TW Annual Production Scales?", APSRC, 2022 (Invited Plenary)
- Pei-Chieh Hsiao, Daniel Chen, Chris Huang, Wenxin Shi, Renate Egan, and Alison Lennon, "Cell-to-Module Analysis of Copper-Plated Silicon Heterojunction Modules with 23.17% Efficiency" APSRC, 2022.

Advanced PV 2030 Symposium

- A. Lennon, "Will Contact Formation Economics be the Determining Factor in Next Generation Silicon Solar Cell Technology Adoption?" (Invited Presentation)

SuperSolar Annual Conference 2022

- A. Lennon, "Metallisation and Material Sustainability for Silicon Photovoltaics" (Invited Presentation)

ARENA ReWired Podcast

- https://arena.gov.au/blog/smashing-solar-records-with-sundrives-vince-allen/

COP26 ARENA Talks: Australia's Brightest Energy Startups Driving the Transition

- https://www.youtube.com/watch?v=Syjm1gyaavI&t=5s

Australian Financial Review Tech Zero Podcast

- https://www.afr.com/companies/energy/dropping-out-of-uni-was-the-best-thing-this-solar-pioneer-ever-did-20221007-p5bnyn

Blackbird Sunrise Startup Event

https://www.youtube.com/watch?v=gU64n0gqG28

UNSW Research Translation Expo

- https://newsroom.unsw.edu.au/news/general/unsw-sydney%E2%80%99s-ground-breaking-innovations-display-research-translation-expo
- https://www.industryupdate.com.au/article/copper-solar-cells-fly-ash-paint-unsw-start-ups-show-expo

NSW Circular Renewable Energy and Chemical Engineering Networking Event

- A. Lennon, “A Local Company Breaking World Records and Planning to Manufacture PV Modules in Australia” (Invited Speaker)

UNSW RESOC Careers Fair

UNSW RESOC Webinar – Solar PV Manufacturing in Australia

Employment Statistics

This project has directly employed 17 additional employees at SunDrive, bringing the total company count to 22 employees at the end of this project. This includes 6 additional engineers to undertake the development of cell and module R&D and 6 mechanical and/or mechatronic engineers to enable advanced manufacturing for SunDrive’s tools. Additionally, as part of company administrations and management, SunDrive has acquired a chief scientist, an operations manager, a senior data analyst, a financial manager, and a strategic advisor.

Modern Slavery Statement

SunDrive has a modern slavery policy that applies to all employees, contractors, and agents (collectively Employees) directly and indirectly employed by SunDrive Solar Pty Ltd ABN 46 169 736 752 (SunDrive). It also applies to SunDrive suppliers and business partners (collectively Business Partners) and any other entity which is bound to follow this policy by the terms of an agreement with SunDrive.

SunDrive is committed to acting ethically and with integrity in all business dealings and to preventing modern slavery in our business or our supply chains.

Should SunDrive become aware that any Business Partner does not meet the Modern Slavery Supplier Code of Conduct, SunDrive will engage directly with the supplier and develop an action plan to eradicate the practise in a transparent, timely and efficient manner. Should the Business Partner be uncooperative, the appropriate action will be taken, including terminating the business relationship, if necessary, by SunDrive.

Lessons Learnt

Lessons Learnt Report: SunDrive's Start-up Experience

Introduction

SunDrive is a technology start-up company currently based in Kirrawee, NSW. The company's overarching goal is to realise the full potential of solar photovoltaics (PV) and accelerate the uptake of solar energy around the world. The technology at the heart of SunDrive is an alternative to traditional silver-based metallisation for industrial solar cell manufacturing that completely replaces silver with copper – a metal that is approximately 1000x more abundant and 100x cheaper than silver.

As the international community pushes towards TW-scale solar production capacity, the criticality of minimising cost by using cheaper and more abundant materials for solar PV generation is an increasingly important issue. Furthermore, with current commercial solar technologies reaching their efficiency limits and next-generation cell technologies demanding even greater silver usage, a growing cost and supply risk presents a significant challenge for the evolution of the solar industry. SunDrive's technology directly addresses this critical issue, whilst also providing performance benefits beyond that achievable with existing silver-based commercial technologies.

Through this ARENA project, SunDrive has demonstrated its cell technology potential and translated this to commercial-size modules, whilst also developing a working prototype production line of its propriety metallisation sequence. This report will provide some details on SunDrive's unique experience of taking a concept from a university laboratory to a commercial venture, as well as the important lessons and takeaways that may help guide other start-ups.

Taking Technology from University to a Start-up

The development of SunDrive's technology began in 2014 with co-founder Vince Allen's PhD at the world-renowned solar research school at the University of New South Wales (UNSW). Along with his supervisors – the late Professor Stuart Wenham and Professor Alison Lennon (now SunDrive Chief Scientist) – the fundamentals of SunDrive's copper metallisation technology were conceived. A critical factor in the decision to start SunDrive and further develop this technology outside a university environment was the support and encouragement provided to Vince by his supervisors. This included the freedom to research multiple different technological approaches in a much shorter period than is usually allowed through university research. Recognising the commercial potential of the technology, they supported Vince heavily during the formative years of SunDrive.

After deciding to further develop this technology outside the university, the next step was to secure the rights to the necessary IP that had been developed at UNSW. New South Innovations (NSi – the knowledge exchange and technology transfer company within UNSW) was supportive in negotiating the licensing of the relevant IP. The licensing agreement allowed SunDrive to obtain an exclusive world-wide perpetual license for a key piece of IP underpinning SunDrive's technology in exchange for a small equity position in the company. It was important during this stage to have the support and backing of those who could see the technology potential at such an early stage of development. SunDrive benefited from having the early support of both seasoned academics with in-depth understanding of commercial solar manufacturing (and the associated challenges/opportunities) as well as those with a stronger focus on commercialisation, who could understand the technology potential from a market perspective.

Securing Initial Investment

With the relevant IP for SunDrive's technology secured, the next step was to attract the necessary investment required to begin developing the technology independently. Initially, SunDrive was self-funding its own technology development out of a garage in Maroubra. However, it was important that the first external investment in SunDrive was from someone who understood the technology, the challenges it was addressing, and the extensive market/business potential should it succeed.

Through Professor Wenham, SunDrive's co-founders met with Chinese-Australian solar scientist and entrepreneur Dr Zhengrong Shi. With an extensive background in both solar technology research and commercialisation (as founder/CEO of Suntech Power, the biggest solar manufacturer in the world in 2010-2011), Dr Shi was perhaps the best person to provide the first external investment in SunDrive. Not only did he understand the solar industry and market opportunity (including personal experience in transitioning a solar technology from university research to commercial solar manufacturing), but he was also acutely aware of the technical challenges that SunDrive's technology was addressing. Suntech aggressively pursued copper metallisation for many years with its Pluto cell technology, but technical difficulties hindered its success. Witnessing first-hand the improvements provided by SunDrive's technology, Dr Shi was convinced in the technology's potential and within a month of visiting SunDrive's garage had agreed to make the first investment in SunDrive in June 2015.

With Dr Shi's international commitments, SunDrive wanted to also bring on board someone deeply involved in the local start-up ecosystem and preferably also from the solar industry. Through UNSW's entrepreneurship team and NSi, SunDrive's founders met with Sylvia Tulloch, founder of DyeSol (at the time, Australia's most advanced solar R&D company that was also listed on the ASX) and an active member of the local start-up community. With her extensive experience in company management, growing her own start-up and investing in other start-ups, as well as government interaction, Mrs Tulloch offered extensive knowledge to SunDrive that would prove invaluable in the following years as it grew and developed its technology. Both Mrs Tulloch and Dr Shi joined SunDrive as board members in 2015.

Technology Development: Start-up vs University

The process of technology development in a lean start-up differs greatly from that in an established research institution or university. As with any independent research venture, this independence has come with numerous advantages and challenges, including:

Advantages

- **Speed:** the iteration cycle for technology development is generally much faster in a self-governed start-up, bypassing a lot of "red tape" and internal policy that can heavily impede the progression of research within many universities. This also applies to collaborations with industry partners, who often operate on a faster iteration cycle than universities. A start-up is often able to better adapt and keep pace with industry partners.

- **Adaptability:** necessity is the mother of invention. With limited resources in the early stages of a start-up company. Everything is built, tested and iterated from the ground up – processes, equipment and even characterisation tools. SunDrive has facilitated this adaptation by hiring its employees from a wide range of fields with varying degrees of experience and expertise. SunDrive has learnt that it is not about your qualifications, it's about your ability.
- **Goal Definition:** everyone within SunDrive is working cooperatively on a singular goal, which simplifies operations and minimises dilution of resources amongst different projects. Whereas a university has multiple disconnected projects competing for equipment access/tool time/funding, a start-up can pool its resources and ability to achieving more clearly defined goals.
- **Wholistic Viewpoint:** whilst university research can often focus on technologies that, while impressive, may never be commercially viable products, technology development within a start-up is all focussed on improving a technology for market. Thus, every stage of technology development is performed with the end-goal in mind – commercialisation.

Challenges

- **Resource scarcity:** especially early on, with limited funding, technology development in a start-up environment can be difficult. Without access to important processing tools and characterisation equipment, adequate technology development can be reliant on self-designed tools (requiring their own iteration cycle) and/or access to external resources through collaboration which can also slow the iteration cycle.
- **Time Pressure:** since a start-up is often under pressure (status of market value proposition, pressure from competitors and investors) to deliver a product to market as quickly as possible, this can often put significant pressure on the iteration cycle. Whilst this does speed up the technology development, it can also impede the ability to provide detailed analysis of results which may help better dictate the development cycle.
- **Learning curve:** there are a lot of things taken for granted in university research that are significant challenges for a lean start-up. Necessary access to sophisticated equipment (processing and characterisation) and services (ultra-pure water, compressed dry air, nitrogen, wastewater treatment) has meant SunDrive has had to build its facilities and services to allow its technology development to progress. SunDrive began its operations in a garage, and now runs a self-designed cleanroom.
- **Anonymity:** the primary downside of operating outside a university is that it removes the safety net of institutional reputation. This can be challenging when sourcing components and early-stage fundraising, particularly through government funding programs. As a start-up, SunDrive has decidedly made a habit of demonstrating its capabilities to investors to compensate for its low profile, building its own track record.

Whilst there are challenges to technology development within a lean start-up, the experience and reputation SunDrive has grown through multiple successful funding rounds has made many of these challenges more manageable.

Forming Collaborations

Collaborations can be essential for a start-up – they not only provide deeper access to the industry they are hoping to enter, but also facilitate faster technology development by providing access to resources that are unavailable without some form of collaboration. Collaboration with research institutions and industry partners has been critical to major advances in SunDrive's technology development, from the scaling of its technology from lab-size to industrial-size wafers right up to the world-record efficiency SunDrive achieved in September 2021.

As a start-up, it can be a daunting prospect to approach larger companies and research institutions. An invaluable asset early on in this process was leveraging SunDrive's existing network of connections to begin those interactions. Maintaining a good network of connections with the university helped in the early stages of technology development and is an excellent resource for initiating conversations with companies/institutions. In the solar industry, companies will often approach research institutions to investigate new technologies for commercial potential. One of SunDrive's current collaborators had approached UNSW with an interest in exploring copper plating, and that connection was passed onto SunDrive.

SunDrive was also able to leverage the connections of its investors with ties to the industry. Once again, companies looking into copper metallisation for their solar technologies were directed to SunDrive through introductions by industry connections (namely Dr Shi in the early stages, who is highly regarded in the international solar community). Whilst having those existing connections to industry and research helped get a foot in the door, having a technology that addresses a big market also helps attract those collaborations.

Fostering these collaborations is essential to maintaining a good trajectory of technology development. Whilst the results of experiments and advances in technology development often in themselves help maintain good collaborations, SunDrive found that having a strong face-to-face presence with regular engagement was an important part of growing new collaborations and forming trusted working relationships. This included the co-founders frequently travelling internationally to visit collaborators for in-person meetings and discussions and maintaining regular correspondence on progress and collaboration goals. Fostering these collaborations as a technology advances is even more important – especially as a company moves from R&D closer towards commercialisation. Often the later stages of technology development require more resources and having trusted relationships with industry partners allows for larger experiments and batch testing.

Growing Capital Investment

Obtaining the necessary funding for further technology progression can be a complicated and time-consuming process. After the initial funding provided by Dr Shi's angel investment, SunDrive began developing its formal pitch deck in preparation for its first institutional investment round. UNSW's entrepreneurship team aided in both refining SunDrive's pitch deck, as well as introducing the company to various potential investors.

An important takeaway from SunDrive's previous funding rounds was the importance of technology demonstration. Just as it worked with securing Dr Shi's investment, inviting potential investors to visit SunDrive's operations and witness the technology first-hand (copper plated solar cells, tool prototypes, etc) is an invaluable way of demonstrating the capabilities of both the technology as well as the team behind it.

With each funding round, securing further investment is dependent on achieving the goals of the previous round. By setting clearly defined goals and metrics to define the success of each round, it is easier to demonstrate to both new and existing investors your track record of technology development. It is important to set ambitious yet achievable goals for each round of technology progression to maintain a successful track record. For a hardware start-up with a comparatively slow iteration cycle compared to high velocity software ventures, it is also crucial to have the support of patient investors with longer term investment aspirations that are willing to support a start-up throughout its commercialisation journey.

Finally, the importance of public investment through government programs should not be understated. Successfully applying for government funding programs not only provides an alternative source of investment, but it also can be highly influential in securing the necessary private investment required for each stage of technology development. Furthermore, public investment in locally developed technologies (especially clean technologies) boosts public awareness that the Australian Government is supportive of local clean technologies and start-ups. This encourages more companies to pursue clean technology ventures, thus supporting the growth of the entire Australian industry landscape.

Summary of Lessons Learnt and Future Outlook

Overall, there are a number of key takeaway's from SunDrive's start-up experience that may be of benefit to other clean technology ventures. While every company is different, there are parallels with every start-up experience. The main lessons from SunDrive's experience are:

1) Early on have (i) someone in your corner who deeply understands the technology, the challenges, and the international market potential (in SunDrive's case, Dr Zhengrong Shi), and (ii) someone on hand who is actively involved in local start-ups who can help with legal, finance, accounting, management - ideally with experience in the same field (in SunDrive's case, Sylvia Tulloch).
2) When spinning a technology out of a university, maintain those connections and relationships. Universities can be an invaluable resource in supporting early-stage start-ups through support, guidance and providing connections to potential collaborations and future recruits. Universities can also help secure government funding through collaborative projects.
3) When it comes to building the team, SunDrive has noticed that ability usually means more than qualifications. Technology development can benefit from experience outside the field that the technology may be designed for.
4) Foster new collaborations through a strong face-to-face presence and regular engagement. This helps build a trusted working relationship, which will allow sustained collaboration as a technology grows and resources required increase.
5) Demonstrating a technology firsthand means more than a good pitch. Let investors and collaborators see the capabilities of both the technology as well as the team behind it.

6) Set technology goals for each round so that each subsequent funding round is off the back of a successful previous round with a proven track record.
7) A mix of public and private investment is vitally important. Not only does one assist in securing the other but public funding can provide greater public support and awareness of novel technologies that can boost the market potential in Australia.

In Australia, support for clean technologies has been growing significantly in recent years. There is a general consensus towards sustainable practices and carbon neutrality in the wake of recent international climate reports and net zero commitments. The Covid pandemic has also shined a spotlight on issues such as energy security and bolstering local supply chains. With growing public support for sustainable technologies, and big cleantech investment funds being raised internationally (Breakthrough Energy Ventures, Lowercarbon VC), the future for investment in clean technologies is bright. With more government support, Australia could be home to a revolutionary new industry to support the country's transition to a net zero economy.