Pushing the limits of shingle heterojunction module performance, cost and sustainability

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Abstract

Recent developments have already proven the potential of shingle heterojunction modules, particularly adapted to new emerging PV markets where both high efficiencies and aesthetics are mandatory. Indeed, such an interconnection configuration can be easily applied on a large area and on high volumes with excellent overall module reliability [1,2,3]. But despite these very promising outcomes, silicon heterojunction (SHJ) shingle technology has not yet fully met expectations in terms of performance and cost competitiveness, mostly because of the SHJ intrinsic cell limitations. The efficiency losses linked to the cut-edge generated at cell level and the large amount of silver needed to compensate for the increased line resistance (deported busbar) are some of the remaining hurdles that need to be addressed to fully consider SHJ shingle for the next generation of PV products [4]. However, innovative and very promising solutions are proposed to tackle these limitations, and the main outcomes are detailed in this paper. Furthermore, the unique combination of SHJ and shingle allows a large window of optimisation at interconnection level, with the possibility to integrate thin and ultra-thin wafers, and also to drastically reduce the electrical conductive adhesive (ECA) consumption or cell-to-cell overlap, without impact on module performance. All these technological improvements contribute to enhancing the already high attractiveness of SHJ shingle technology, and to close the gap with industrial, economic and sustainability requirements usually considered for large-scale deployment of such panels.

Introduction

Shingle interconnection is gaining more and more interest as it combines high-efficiency potential and improved aesthetics due to the denser silicon integration within the final module panel [5,6,7,8]. Commercial products are already industrially available, mostly integrating PERC (Passivated Emitter and Rear Contact) cell technology (panels from Solaria or SunPower, for example). However, the latest high-efficiency PV cell architectures, mostly relying on a high level of passivation, are not an obvious match for such a module configuration. This is particularly the case for silicon heterojunction (SHJ) devices, for which optimised integration needs to overcome two major intrinsic limitations:

"...significantly higher efficiencies can be achieved with the application of highly promising post-cut-edge repassivation solutions."

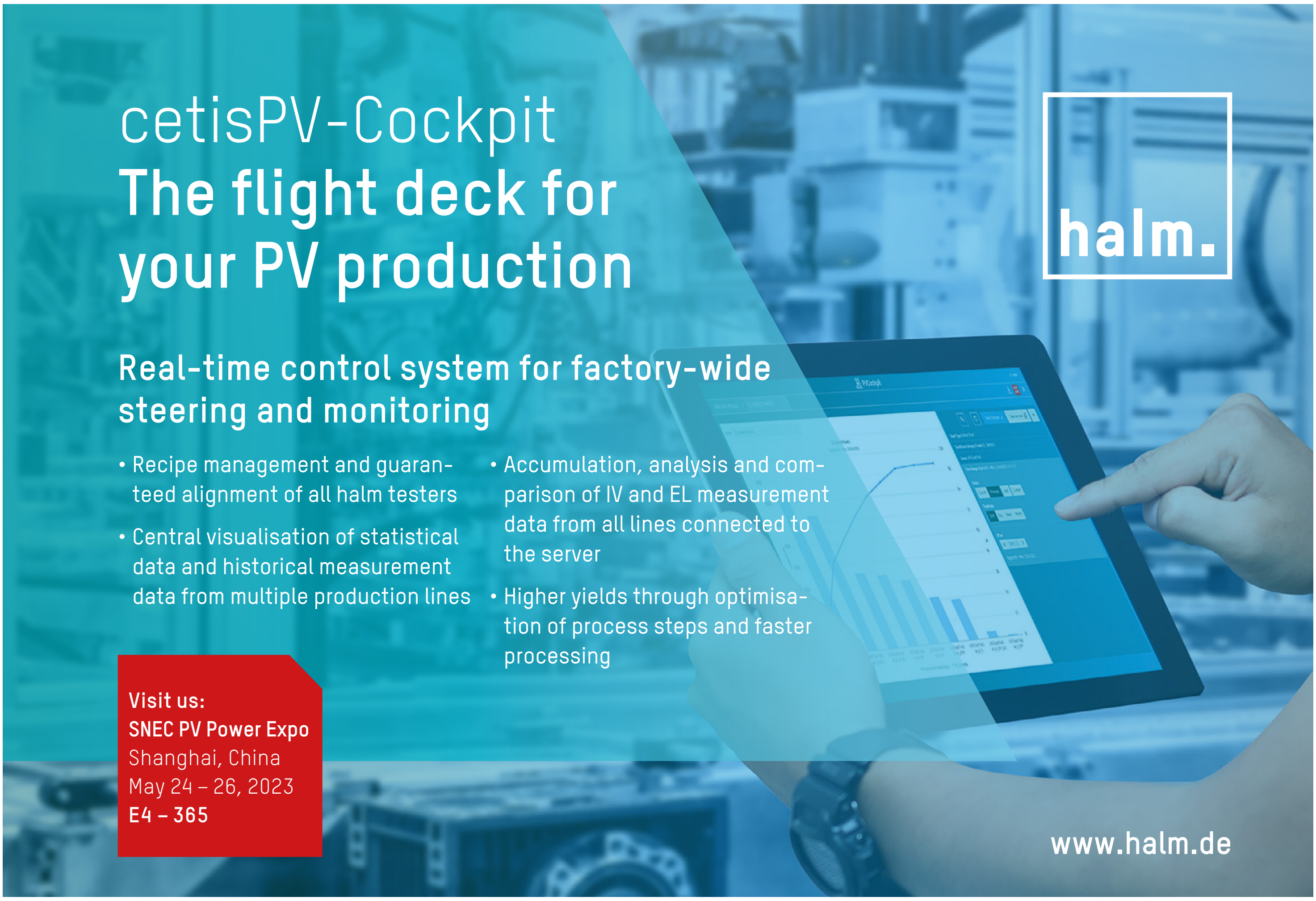
1. High efficiency losses after cell cut in shingle stripes (up to 1% Abs losses can be observed on final cut-cells).

2. High metal resistance linked to the deported busbar metal pattern, and the high resistivity of low-temperature silver metal paste.

While it has already been demonstrated that high-performance shingle modules with excellent reliability can be manufactured with SHJ-based cells [9], it is clear that innovative solutions are needed to further enhance the attractiveness of such SHJ shingle modules. This is true not only for costs, but also for overall long-term sustainability of the technology, which cannot be neglected if very large volumes of such modules are expected in the coming years [10]. So, how can the current limitations highlighted for our SHJ shingle modules be further addressed?

Firstly, at cell level, we will show that significantly higher efficiencies can be achieved with the application of highly promising post-cut-edge repassivation solutions. Indeed, we demonstrate that a low-temperature AlOx layer with a proper activation process could lead to more than 90% performance recovery. SHJ shingle cut-cells fabricated with such an edge-passivation process reached efficiencies very close to the mother cell before cut. To address the metal resistivity issues, an increased amount of silver paste is generally deposited to reach a sufficiently high final line aspect ratio. This is obviously not acceptable and we will show that a switch towards copper metallization solutions seems unavoidable in the near future.

Secondly, we will also show that due to the unique properties of the SHJ architecture, there is still room for optimisation at both interconnection and module levels. The excellent adhesion of ECA (Electrical Conductive Adhesive) on the cell TCO (Transparent Conductive Oxide) allows, for example, a drastic reduction of ECA consumption and/or the move towards very aggressive cell-



to-cell overlap (down to 0.5mm, as shown in this paper). Furthermore, the symmetric and low-temperature configuration of the SHJ makes it particularly compatible with the use of thin and ultra-thin wafers, and very promising modules integrating 120μm- and 90μm-thick wafers have been generated, all showing even better reliability outputs than the reference modules built with standard 160μm-thick cells!

High efficiency, aesthetics, low cost and sustainability…can we really have it all? Compromises will probably be needed, but as we will show in this paper, with such progress margins left at both cell and module levels, we confirm that the already huge potential of the SHJ shingle technology can be even further optimised to propose high-quality products complying with industrial, commercial and environmental requirements in the near future.

An already mature technology

As shown in a previous PVI-dedicated study [3], large-area modules integrating shingle heterojunction cells have been successfully manufactured in collaboration with Applied Materials–Baccini for the stringing part. Electrical output powers of up to 400W were measured on the best modules [11], but it was also recently shown that extremely good technology repeatability could be achieved with production of higher volumes of panels, all showing very similar power outputs. This is the case, for example, for the modules presented in figure 1, where smaller module sizes were targeted (60 M2 equivalent final dimension) in a glass–glass configuration. As shown with the final power measurements, all modules built are functional, but the most impressive aspect is the high uniformity of the performance achieved, proving the very good repeatability of the whole fabrication process (from initial cell to final module). The slightly better output powers observed for the first two modules are only linked to the lower optical wavelength cut-off encapsulant used for these modules, allowing in particular an increase of the UV (Ultra Violet) light harvesting within the panel.

Such outcomes are still obtained while maintaining very high reliability, with limited power losses for up to 800 TC (Thermal Cycling aging tests conducted between -40°C and +85°C), which is impressive and even better than what is generally observed for standard ribbon interconnection SHJ panels. It can be seen that such good reliability results are maintained even when using significantly thinner wafers within the module. The specific case of thin-wafer integration will be detailed in the next section. It is also important to observe that high bifaciality has been maintained on the fabricated shingle modules (typically ~85% bifaciality) and this can be key if the final applications will benefit from a high level of albedo once installed. Indeed, the first monitoring data extracted from such bifacial modules clearly show the benefit of the high-performance SHJ shingle modules when compared with other technologies such as PERC, for example. The higher performance ratio (PR) demonstrated is also linked to the better module bifaciality coefficient, demonstrating that even for shingle configuration, increased performance can be observed with proper management of the back of the module.

Possible improvement remains at the interconnection level

Even though very promising outputs have already been demonstrated for an SHJ shingle configuration, the latest developments conducted at CEA-INES showed that there is probably still room for further improvement, especially at the interconnection level.

Firstly, due to the very good adhesion of ECA observed on the upper TCO layer, we tried to reduce the total amount of ECA deposited on each individual shingle tile. Indeed, even if low quantities of ECA are considered, the current price of such products remains high. Consequently, if even lower amounts of ECA could be achieved

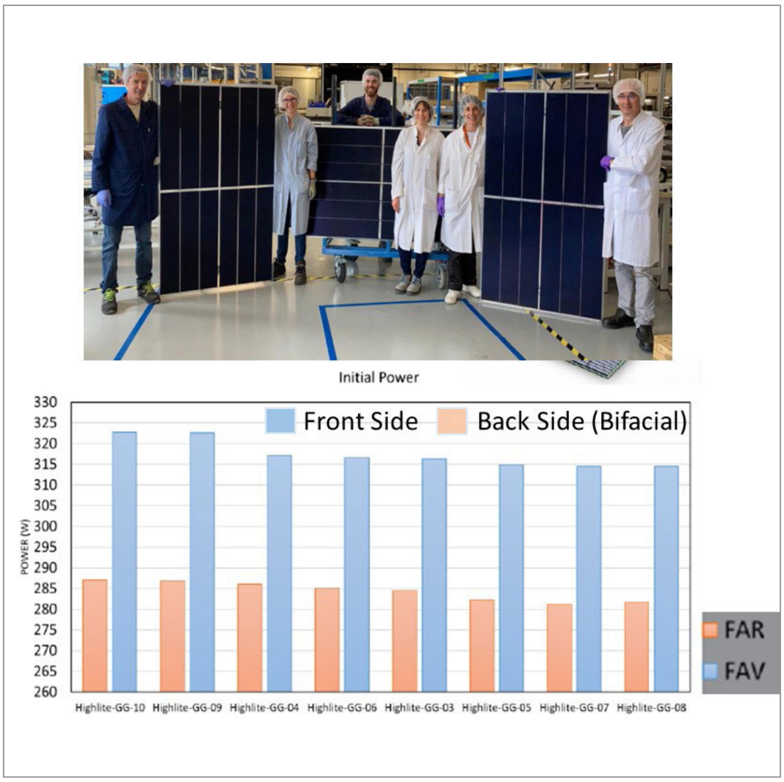


Figure 1: SHJ shingle module typical mini-production batch outputs. Top: Picture of the CEA-INES module research team with large area shingle modules as manufactured on the pilot-line. Bottom: Ouput power (in W, front and back-side illumination values provided) measured for the latest SHJ shingle panels produced, showing extremely high repeatability and uniformity of performance.

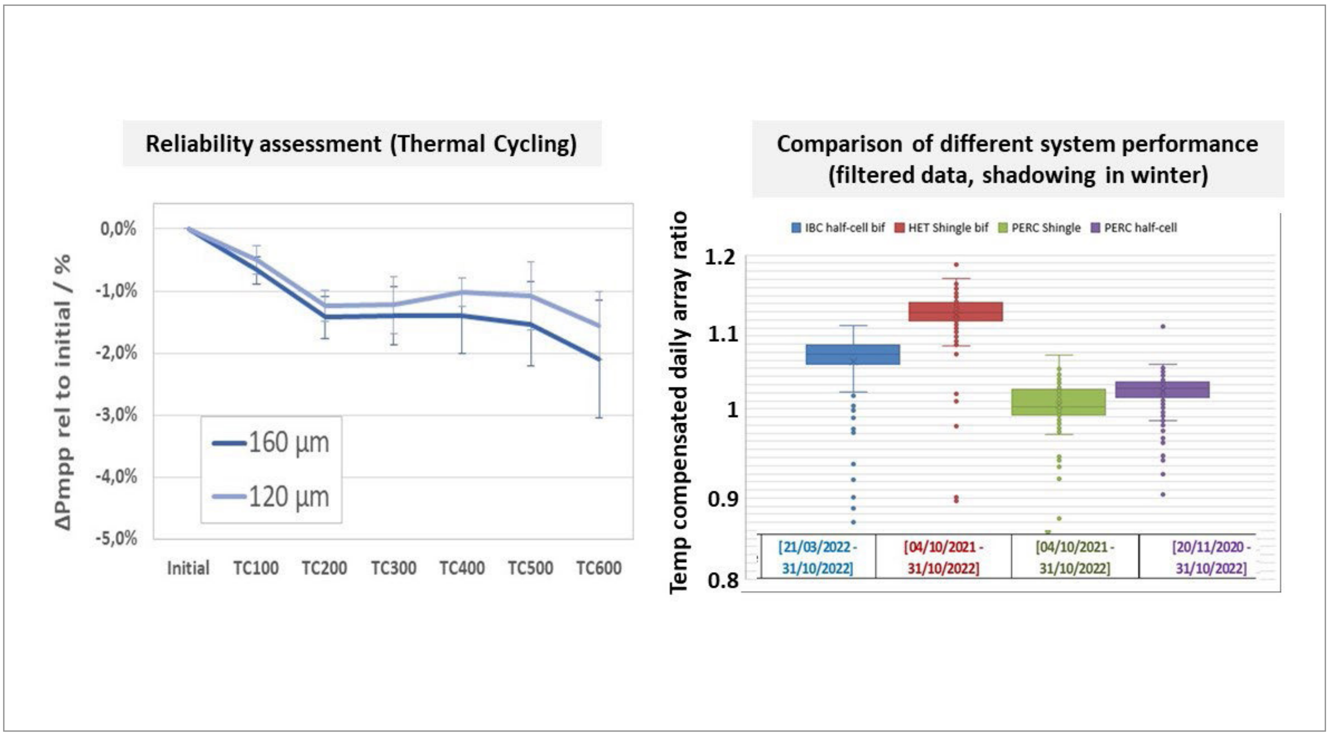


Figure 2: (Left) Outstanding reliability demonstrated for SHJ shingle modules, even for thinner wafers. (Right) Temperature corrected performance ratio (PR') for several module strings monitored at CEA Cadarache, showing improved performance for the SHJ shingle modules, due to both high initial performance and the high bifaciality coefficient of the module installed.

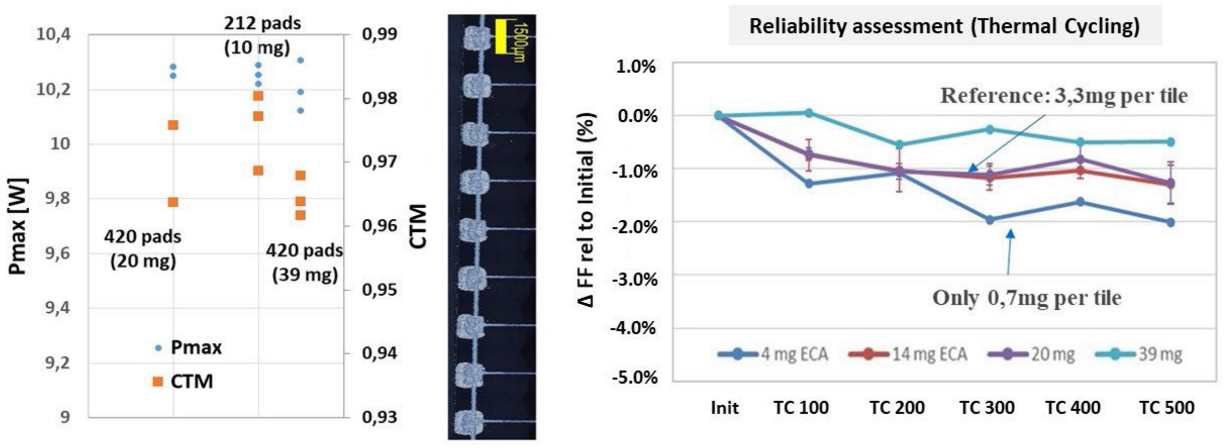


Figure 3: Impact of the deposited ECA mass for shingling. (Left) Negligible impact on mini-module performance (Pmax) of ECA reduction. (Right) Very high reliability maintained even for the very low deposit conditions.

without any impact on either module performance or overall reliability, this would help to further reduce the cost of the final product. Experiments were conducted on mini-module configuration, varying the ECA weight between high-deposit conditions (39mg per full cell, so ~6.5mg for a single tile) to very low deposits (only 4mg per full cell, so only ~0.7mg for a single tile). The typical ECA deposit for a standard module is 20mg for each full cell, so approximately 3.3mg for each individual tile. As shown in figure 3, negligible impact on module performance is observed when lowering the ECA amount deposit, which is a promising outcome, meaning that the series resistance is not increased with the reduced quantity of paste used. Besides, the most outstanding results come from the monitored reliability, as extremely good module performance is maintained for all ECA deposit conditions. Even if the highest ECA deposits feature slightly improved reliability after TC (Thermal Cycling) aging tests, less than 2% relative fill factor (FF) losses can still be achieved after up to 500 cycles even for the lowest ECA deposit. Power losses (not shown in figure 3) follow the same trend, with again less than 2% relative losses for up to 500 cycles, which remains well below the usual normative threshold of 5% power loss tolerated.

Secondly, in addition to ECA optimisations, another way to address cost issues is to evaluate whether more aggressive cell-to-cell overlap could easily be achievable for the interconnection scheme. Indeed, with reduced overlap, higher module power could be achieved due to the increased PV conversion surface, which will ultimately lead to lower costs (more W for a similar cell and module material cost…). Again, several mini-modules were processed, varying the cell-to-cell overlap from 1mm (the standard value for our developments) to a very aggressive value of only 0.5mm. This reduction was very challenging, as for such a small overlap, very accurate alignment must be ensured for many successive processes: cell metal print, cell cut, ECA deposition and cell positioning on final strings. Initial experiments showed an increased number of failures during module fabrication. SEM analysis of the interconnections (figure 4) showed that while reducing the overlap, the ECA was spreading over the edge of the cell, leading to electrical shunts. However, on the working modules, there was clear evidence of a power improvement due to the reduced overlap, mainly linked to the increase of the current\ to the increased PV surface, as expected. However, even if reliability remains within the usual normative requirements for such modules, a clear degradation is measured in thermal cycling tests when shifting from 1mm to 0.5mm. To overcome these issues, it was decided to modify the metal busbar pattern design, allowing extra open space between two successive tiles and relieving the alignment constraints for ECA printing. If aggressive alignment constraints still occur on the stringer cell placement, this simple optimisation significantly improves both manufacturing outcomes (higher numbers of fully functional modules generated) and reliability. As shown in figure 4, the reliability gap between reference modules and 0.5mm overlap modules

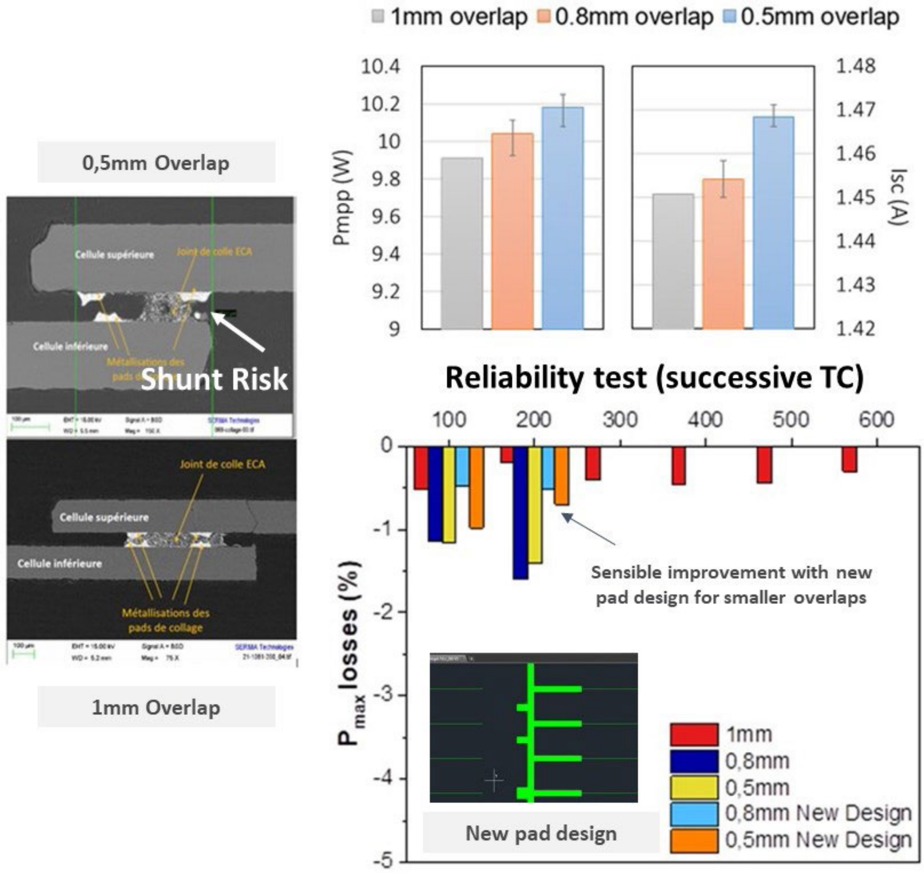


Figure 4: Impact of cell-to-cell overlap reduction. (Right) SEM pictures highlighting the increased shunting risk with reduced overlap – (top) Pmpp improvement shown at module level for reduced overlaps; (bottom) reliability assessment of different overlap configurations. Good reliability maintained for the 0.5mm overlap with newly adapted metal design.

has been significantly reduced, and promising preliminary results are demonstrated up to 200 cycles (less than 1% power degradation for the 0.5mm overlap case). Nevertheless, there is still optimisation work to be done to fully consider the 0.5mm overlap for production. In the meantime, a 0.8mm overlap seems fully compatible with all integration constraints and could already be a significant lever for improvement of the technology.

Sub-120μm wafer integration in shingles

Thin-wafer integration has been a major achievement for SHJ shingling technology. The symmetrical architecture of SHJ makes it possible to achieve high performance even on very thin wafer substrates, as demonstrated by several studies conducted at CEA-INES and very recently by LONGi, with an impressive efficiency of 25.68% obtained on 56μm-thin wafers presented during WCPEC-8 [12]. For shingle evaluation, we screened three different wafer thicknesses: standard 150/160μm wafers, thinner 120μm wafers and very thin 90μm wafers. The objectives with such thin wafers were to assess the feasibility of shingle integration and to open up a new field of applications due to the extra flexibility of the wafers. Furthermore, the use of thin or ultra-thin wafers is consistent with cost reduction and increased global sustainability goals, where wafers are a major contributor in both cases.

Work has been conducted, first, on 120μm-thick wafers, with very promising outcomes, as already shown in figure 2. Fully operational large-area modules have been manufactured, with the thermal cycling qualification passing 3xIEC standard requirements. Then, a set of mini-modules was produced, integrating all three main wafer thicknesses mentioned, with the main objective this time to assess the impact of even thinner wafers, down to 90μm. These ultra-thin shingle cells were all processed on the CEA-INES production pilot-line, with a promising 22.2–22.3% average range efficiency achieved. Even though the volume produced remains small, with such medium-scale processing conditions no increase in breakage rate was observed during either stringing or lamination. However, the laser-

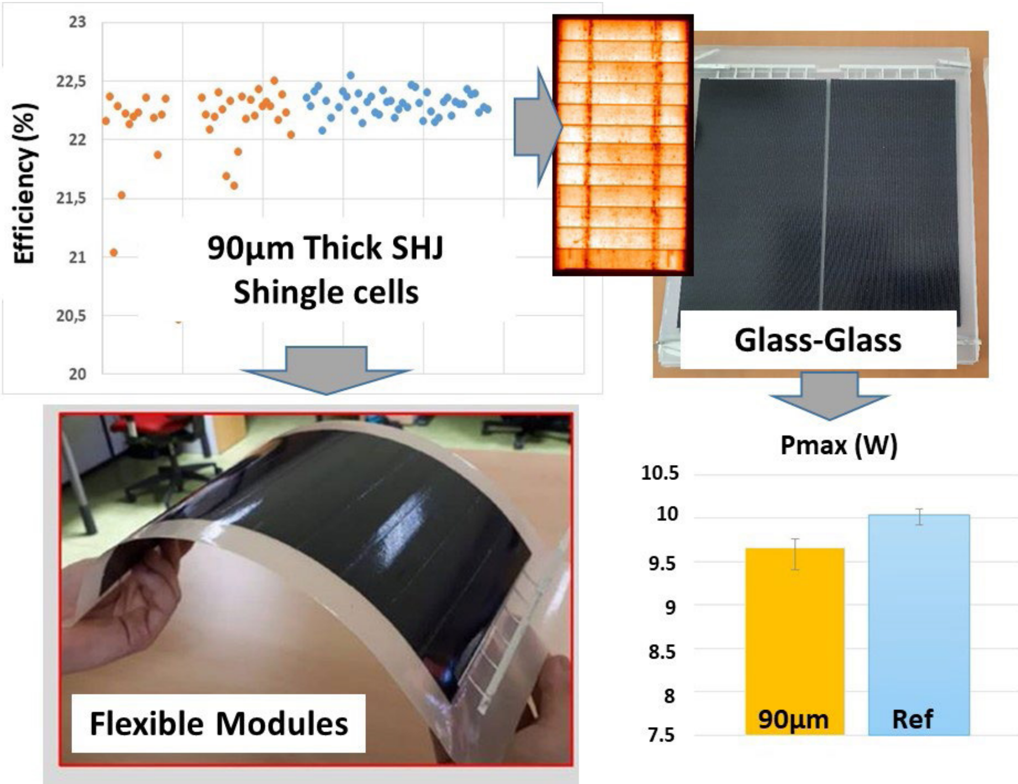


Figure 5: Illustration of different cell and module outcomes integrating 90µm-thick SHJ shingle cells. (Top left) Typical efficiencies achieved on the production line with 90µm wafers. (Bottom right) Typical mini-module output powers achieved for 90µm wafers and compared with the usual 150µm reference.

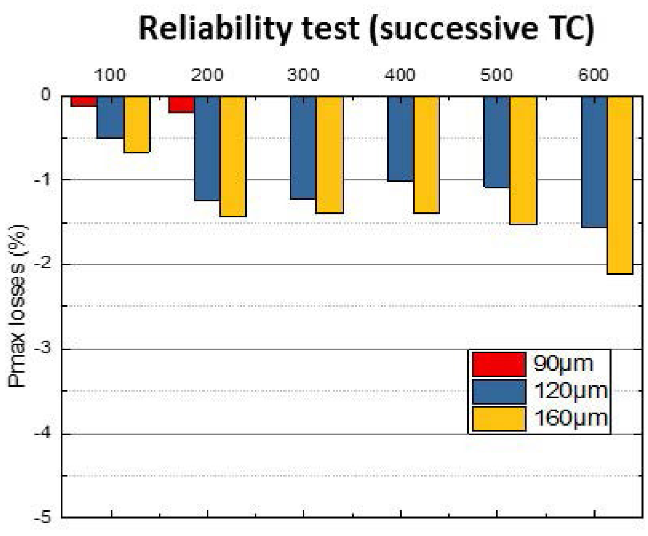


Figure 6: Thermal cycling reliability assessment for modules integrating different wafer thicknesses (glass–glass configuration). Improved reliability was demonstrated with a reduction of the wafer thickness integration for the SHJ shingle module configuration.

cutting process had to be slightly adjusted to ensure a low breakage rate during the cut of the initial full cell into six shingle tiles.

Module results achieved were in line with expectations, with final output powers slightly below the 160µm reference for the modules integrating the 90µm wafers, mostly due to lower initial full cell efficiencies. But similar Cell to Module (CTM) values have been calculated, showing that no degradation of the interconnection quality in particular was observed after integration. Furthermore, electroluminescence (EL) observations did not reveal any cracks or degradation within the module upon processing. In parallel, low-weight and flexible modules were specifically designed using an adapted bill of materials for module assembly. Several modules were produced again in these conditions, combining a high degree of flexibility and very pleasing aesthetics, as shown in figure 5. These modules benefit from the intrinsic strength of the shingle interconnection due to the superior mechanical properties of ECAs and their strong adhesion on the TCO layer. So, SHJ shingle technology, coupled with the increased flexibility of thin wafers and a carefully selected bill of materials, could clearly pave the way towards many novel PV module applications.

Finally, reliability tests were conducted on the mini-modules in a glass–glass configuration with different wafer thicknesses, as presented in figure 6. A power loss well below 5% was observed for up to 200 cycles, which was maintained up to 600 cycles on 120μm and 160μm wafers. Moreover, the most impressive result is the fact that the power loss was reduced even when reducing the wafer thickness. This very impressive result was probably achieved due to the higher degree of flexibility of the thin wafers, which can better absorb the mechanical mismatch induced by the successive thermal cycles conducted during TC (further measurements are in progress). According to these preliminary results on thin wafers, a completely new progress path for shingle SHJ technology was evidenced, in terms of potential for cost reduction, improved reliability and alternative applications.

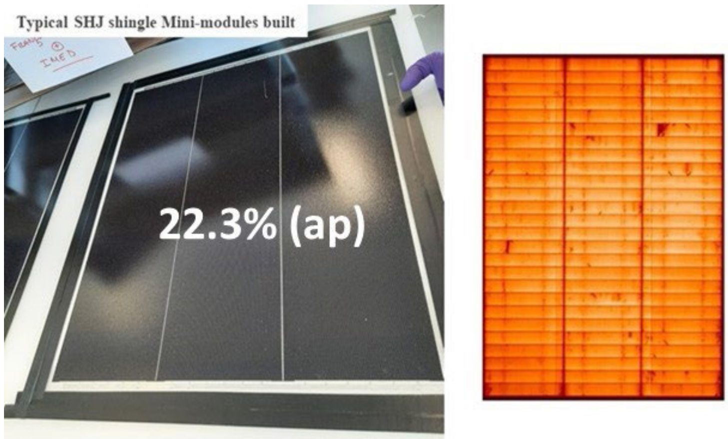
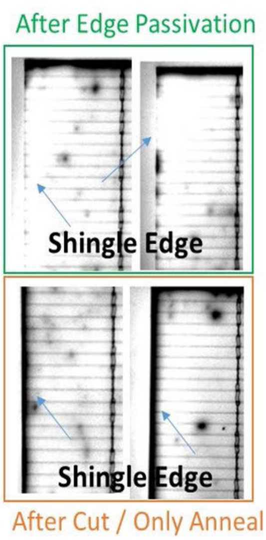


Figure 7: Photo (left) and EL (right) of a module prototype (three strings of 26 tiles) demonstrating the capability of reaching a high efficiency of 22.3% (aperture measurement) for the SHJ shingle configuration. Performances are still mostly limited by cut-edge parasitic recombination (no edge passivation on the integrated tile for this module).

Efficiency boost with a cell edge-passivation process

As shown in the previous sections, promising module powers and efficiencies are already achievable with current cell and interconnection processes. Also, a very promising 22.3% module efficiency was obtained recently on medium-size modules (figure 7). However, as mentioned previously, a significant performance loss is still observed because of the edge defectivity generated during the full cell cut in smaller shingle dimensions [13]. This is particularly a problem for the SHJ architecture, which generally presents a very high Voc on full cells, due to the high quality of passivation of the amorphous layers used.



Best Cell Output (AlOx 15nm)

	Voc (mV)	Isc (A)	FF (%)	Eff (%)	Delta Eff (%)
Initial	740,6	9,18	81,2	22,59	
Post Cleavage	734,3	9,132	78,3	21,48	-1,1
Passivation	741,6	9,136	81,1	22,48	+1,0

~90% Eff recovery

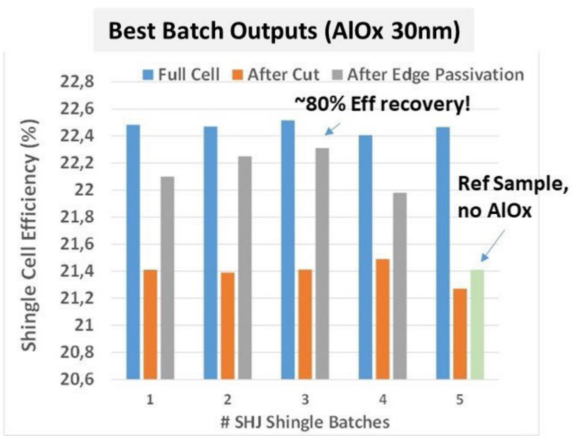


Figure 8: The low-temperature AlOx-based edge-passivation process developed. Significant improvement of the edge PL signal is observed, which translates to high recovery of performance as measured on the cut-shingle cells after deposition of the passivation layer. Up to 90% performance recovery was demonstrated on the best cells.

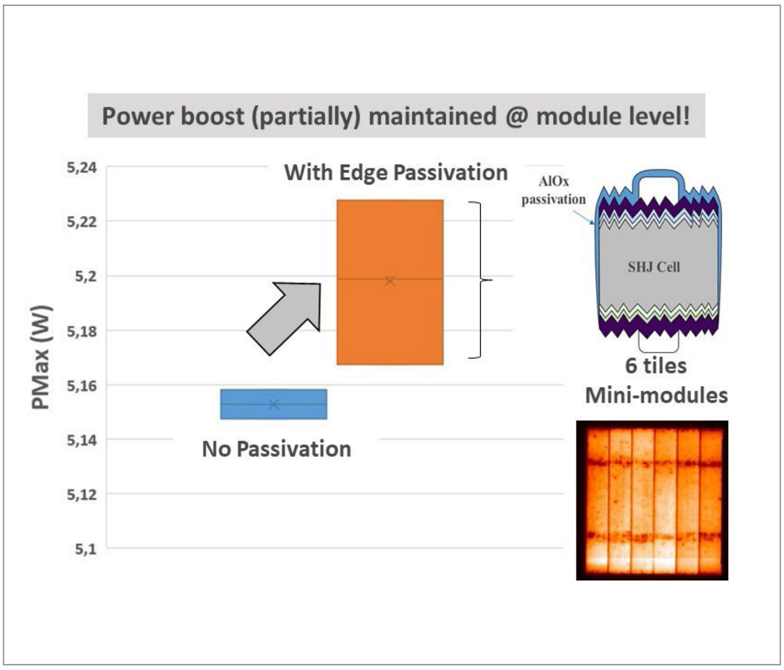


Figure 9: Average performance measured for glass–glass SHJ shingle mini-modules (three modules for each configuration), highlighting the performance improvement achieved with the integration of the passivated shingle tiles (as illustrated in the schematic on the right). No apparent degradation of interconnection quality was observed, as shown, for example, on the PL image provided.

To improve cut-cell performance, an additional edge-passivation process is required [14,15]. At CEA-INES, we have developed low-temperature (~100–130°C) aluminium oxide (AlOx) layers, deposited by Atomic Layer Deposition (ALD) and compatible with the SHJ architecture constraints. The annealing and activation of the deposited layers is ensured by optimised light-soaking treatment, which is a process already widely implemented in most SHJ production lines. Details can be found in [16] and only the most representative results will be reported in this paper. With a fully optimised process, we demonstrated that highly significant efficiency recovery is obtained on the shingle cells undergoing such an edge-passivation process. This is clearly shown on photoluminescence (PL) observations and also on cell electrical outputs, with up to 90% performance recovery demonstrated for the best devices. The repeatability of the process described in this paper has also been proven on repeated batches, with higher volume of cells processed (more than 100 cells processed in total), proving the robustness of this passivation process. Further developments are ongoing to improve the AlOx layer quality and its industrial compatibility, by reducing the layer thickness and increase even further the passivation potential. Transferring the layer deposition from ALD to Plasma Enhanced Chemical Vapor Deposition (PECVD) tools is also an objective to reach high-volume wafer treatment, as required for the PV industry.

The passivation quality of this process was demonstrated with AlOx layers down to 15nm and, as mentioned previously, work is ongoing to further reduce this thickness. This is important, as, for now, the process consists of full-wafer deposition of the layer, meaning that this insulating AlOx covers both TCO and metal, and could potentially degrade ECA adhesion or overall interconnection conductivity. This must be properly assessed, and to that purpose, a set of dedicated mini-modules has been built, integrating shingle SHJ cells with the AlOx passivating layer. EL characterisation conducted on finalized modules do not show any apparent degradation of the quality of the interconnection with these devices (figure 9). This was only partially confirmed by IV electrical measurements. Indeed, an improved output power was shown for all the modules with cell edge passivation, which is the first confirmation that performance improvement achieved at cell level can be maintained at module level. Power gain is linked to both improved FF and Voc on the passivated modules, as expected. However, modules with a passivated edge also showed a greater performance dispersion than the reference modules, indicating that further integration optimisation is still probably needed to tackle the additional challenge brought by the presence of the AlOx layer and then to fully profit from the higher initial cell efficiency potential. Results presented are nevertheless very promising, as this is the first experimental validation that the passivation process proposed in this paper should be suitable with all cell and module production constraints. New experiments are planned and an overall reliability assessment of the module produced will be performed during the next few months.

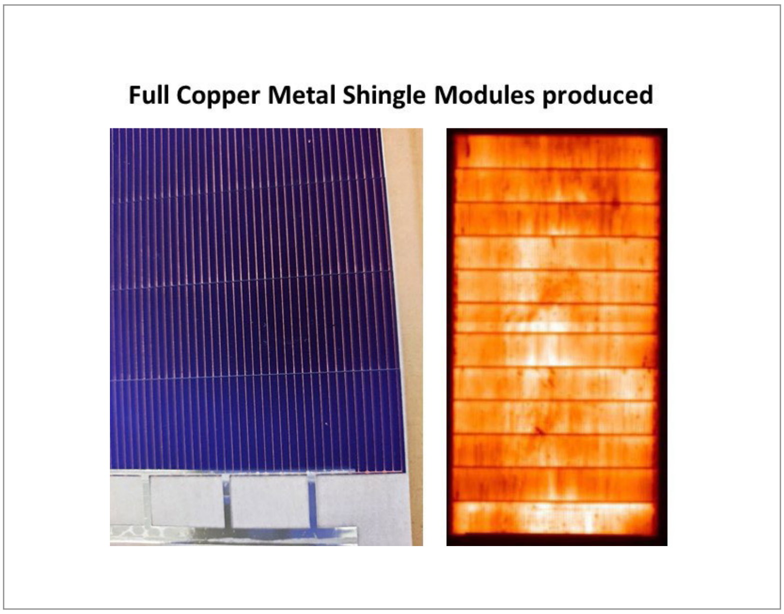


Figure 11: The first SHJ shingle modules successfully assembled with full copper-paste metallization

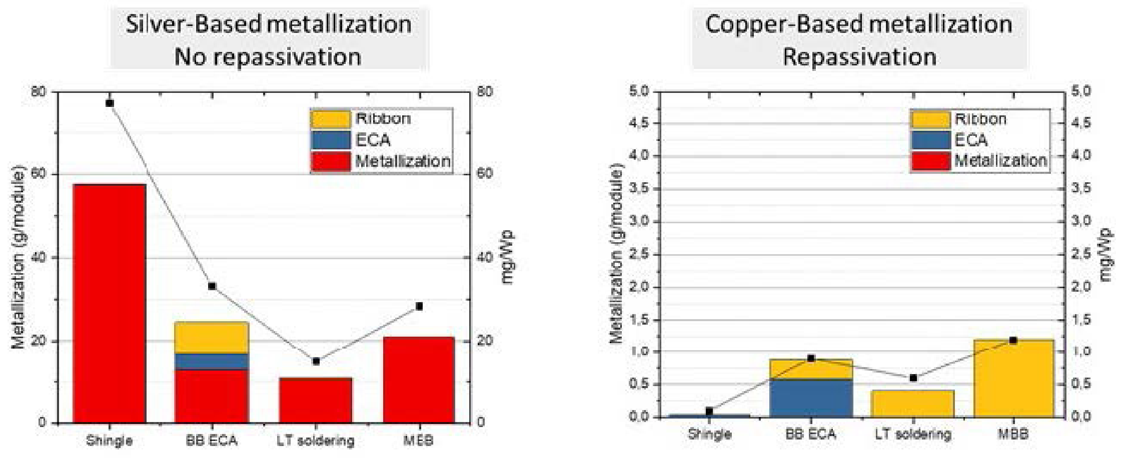


Figure 10: Projected silver consumption for different module cell and interconnection configurations. A switch to copper metal solutions is clearly beneficial, especially for an SHJ shingle configuration, which becomes highly competitive compared with other technologies.

Towards copper-based shingle metallization?

It has already been shown in previous sections that silver usage at interconnection level can be reduced to very low deposits without impacting the quality of the interconnection. However, the main silver consumption will remain in the cell, as a larger amount of silver is needed to compensate for the shingle-specific metal grid design. Indeed, with the deported busbar, the length of the metal lines is approximately twice the length of conventional cells and the impact on performance is tremendous if no specific optimisation is applied. The current SHJ shingle technology is thus significantly impacted in terms of cost competitiveness with regard to the usual alternative module solutions (Figure 10). Even though progress has been made recently in the reduction of silver-paste deposits, the amount of silver needed to maximise cell performance will always remain greater than that needed for more usual cell architectures (busbar SHJ, TOPCon, PERC, etc). Consequently, a switch to an alternative metallization scheme seems unavoidable and the most promising candidate for now is the switch to copper, either using copper paste or introducing copper plating [17].

But, is this really an issue for the future of shingle? Probably not. Indeed, for any solar cell technology, as made clear by several recent publications, the use of silver for metallization will not be possible for the Terawatt-scale production projected over the coming years [18] and a shift of the whole solar industry towards a silver-free metal solution will happen over the next few years. As shown in figure 10, this will benefit even more the SHJ shingle configuration. With proper management of the edge-related performance losses (see previous section), projected simulations/calculations suggest that the shingle module configuration can actually become the most attractive in terms of overall sustainability and once again become very attractive cost-wise.

Still, is a shingle interconnection compatible with copper? We successfully achieved the first functional modules integrating SHJ cells produced with copper-paste metallization (as shown in Figure 11). If this preliminary result shows the compatibility of full copper metallization with a shingle configuration, dedicated reliability tests conducted (not shown here) indicate a significant degradation of performance after only a few thermal cycles, probably linked to uncontrolled oxidation of the copper. Further optimisation is thus needed, and new tests are required with alternative copper pastes (or copper plating) and adapted ECA. The most promising combination(s) should be identified soon, and shingle modules will also benefit from general progress in copper integration in a standard module interconnection configuration.

Conclusions

In this paper, we provide an overview of the current status of SHJ shingle developments conducted at CEA-INES, in collaboration with Applied Materials–Baccini for the stringing part. Although the technology developed already shows a high degree of maturity and industrial readiness, which is also confirmed by the improved first outdoor monitoring outputs generated, there are still challenges to overcome to realise the full potential of the technology and to propose a cost-effective final product adapted to market constraints. Among the remaining challenges to address, there is the proper optimisation of the cut-edge performance losses and work on global silver-consumption reduction. For edge passivation, a very promising process path is already under development. In terms of the metal concerns, the SHJ shingle configuration will probably need to switch to copper solutions, but this would probably be the case for most of the alternative PV architectures as well. We also showed that the current interconnection scheme could still easily be further optimised to enhance its performance and address cost of fabrication issues. Very impressive results were obtained at module level with extremely low ECA deposits, down to only 0.7mg per tile as demonstrated in this paper. Another major achievement confirmed in the global work presented is the extremely high reliability of the SHJ shingle interconnection developed. Finally, we also highlighted the high (and unique?) compatibility of this SHJ shingle technology with the integration of thin and ultra-thin wafers (down to 90µm). Excellent output powers and impressive reliability were obtained on the different modules produced, opening up a whole new field of potential applications for the technology in the future.

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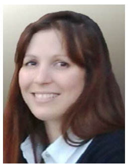
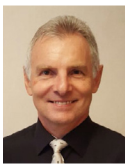
Samuel Harrison obtained his PhD in 2005 in the field of microelectronics, working on advanced CMOS components, and he then worked for Philips Semiconductors on industrial CMOS integration. He joined CEA in 2007, first on microsystems development before his integration into the photovoltaic department in 2009. Since then, his work is focused on heterojunction crystalline cells, contributing in particular to the ramp-up of the industrial pilot-line, while remaining in charge of several research activities on alternative cell concepts.

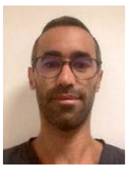


Carolyn Carriere studied chemistry and materials science at Aix-Marseille University in France and holds an MSc in Physics of Materials for Energy. Since 2013, she has worked as an engineer within CNRS (France), University of Sherbrooke 3IT (Canada) and IMEC (Belgium), before joining the PV-module research group of CEA-INES in 2020, to work on innovative technologies.

Vincent Barth received his PhD in 2014 from Sorbonne University in the field of organic photovoltaics, working on the synthesis of small molecules as donor material or as HTL material, and their use in photovoltaic devices. He joined CEA-INES in 2017 to work on PV-module technology. His work focuses on heterojunction module industrial manufacturing, with a specific interest in different interconnection solutions.



Armand Bettinelli received his PhD in 1987 for his work on cofiring of alumina and tungsten at Strasburg University. He worked in the industry as technical manager in the field of high- and low-cofired ceramics, then plasma display panels, all using high-level screen-printing. In 2005, he joined CEA-INES where he holds a senior expert position in cSi-solar cell metallization and interconnection..



Benoit Martel obtained a Master's degree in Material Sciences and Engineering at Grenoble INP in 2009. He started his career in the PV industry at PHOTOWATT as Cells Process Engineer. He joined CEA-INES in 2011, to develop advanced characterisation tools for PV applications. He is currently working as a research engineer in PV silicon defects characterisation and cell process developments.

Hervé Colin specialises in PV system modelling and simulation, monitoring data treatment and analysis, and performance assessment. He has been involved with, or in charge of, projects dealing with PV plant monitoring (monitoring equipment and data acquisition), performance assessment and fault detection/diagnosis, grid connection rules improvement, simulation of various types of PV systems, methods for production estimations, benchmark analysis of bifacial systems, solar road systems operation, floating systems, and agrivoltaic system operation.

Nicola Frasson was born in Montebelluna (Treviso, Italy) in 1993. He received an MSc degree in Science and Technology of Bio and Nanomaterials from Ca' Foscari University of Venice in 2019. He has experience in the biotech and chemical fields, gained during academic research and previous professional positions. He joined Applied Materials in 2020 as Process Support Engineer (R&D), and his focus is on printed electronics, optics, and solar cell metallization.

Marco Galiazzo was born in Padova, Italy, in 1981. He received an MSc degree in Telecommunications Engineering from University of Padova in 2005. From 2006 to 2008, he worked at a startup as Optical Engineer, developing laser sources for material micro-processing. Since 2008, he has worked for Applied Materials Italy (Treviso, Italy) as R&D Manager, coordinating research work in the field of solar cell metallization and module manufacturing.

Enquiries

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