Lamination process and encapsulation materials for glass–glass PV module design

Gianluca Cattaneo[1], Antonin Faes[1], Heng-Yu Li[1,2], Federico Galliano[1,2], Maria Gragert[3], Yu Yao[3], Rainer Grischke[3], Thomas Söderström[3], Matthieu Despeisse[1], Christophe Ballif[1,2] & Laure-Emmanuelle Perret-Aebi[1]

[1]CSEM, PV-Center, Neuchâtel; [2]Photovoltaics and Thin Film Electronics Laboratory (PV-Lab), Institute of Microengineering (IMT), Ecole Polytechnique Fédérale de Lausanne (EPFL), Neuchâtel; [3]Meyer Burger AG, Gwatt, Switzerland

ABSTRACT

In the last few years PV technology has seen continuous improvements, with significant enhancements at the cell and module levels. In addition to the requirement of high efficiency, the long-term reliability of PV modules leads to proposals for innovative module concepts and designs. Meyer Burger has developed a low-temperature wire-bonding technology, known as SmartWire Connection Technology (SWCT), with the aim of offering a cost-effective solution for high-efficiency solar cells while minimizing cell-to-module losses. The introduction of this interconnection design immediately brings new challenges, especially in the selection of an appropriate encapsulant, which must ensure a good processability as well as the required long-term module reliability. The compatibility of the most cost-effective types of encapsulant currently available on the market was analysed in the study reported in this paper. Thermoplastic polyolefin encapsulants with water absorption less than 0.1% and no (or few) cross-linking additives have proved to be the best option for long-lasting PV modules in a glass-glass (GG) configuration. The development of a laminator having a symmetrical structure (two heating plates without any vacuum membrane) has also opened the door to fast lamination processes with cycle times under eight minutes.

Introduction

The majority of today's crystalline silicon (c-Si) PV modules are manufactured in accordance with a glass-backsheet (GBS) module lay-up: 3.2–4mm glass at the front and a polymer-based insulating backsheet (Fig. 1(a)). An aluminium frame is applied around the module to increase mechanical stability. The mono- or polycrystalline Si solar cells with busbars (BBs) are electrically connected with tinned copper ribbons using a high-temperature (T > 220°C) soldering process (Fig. 1(b)). The most popular encapsulant for this PV module design has long been (and still is) the copolymer ethylene vinyl acetate (EVA).

This type of module has been operational in the field for over 30 years, and several failures have been discovered, observed and investigated [1–3]. Failure mechanisms are often attributed to moisture penetration into the module through the backsheet and the bulk of the encapsulant. When subjected to water and/or ultraviolet (UV) radiation exposure, EVA decomposes to produce acetic acid, which accelerates metallization corrosion [4,5]. Under outdoor conditions, EVA suffers yellowing, browning and delamination, which cause considerable power loss. Fig. 2 shows a GBS PV module with an EVA encapsulant after 20 years' exposure on the roof of a building in Switzerland. Among the observed failures, there is clear evidence of delamination and yellowing, which lead to a total measured power loss of 15%. Potential-induced degradation (PID) has also been linked to EVA formulation and identified as a critical aspect of PV module system reliability [6].

As a response to the need for longer-lasting and higher-efficiency PV modules, significant improvements have been

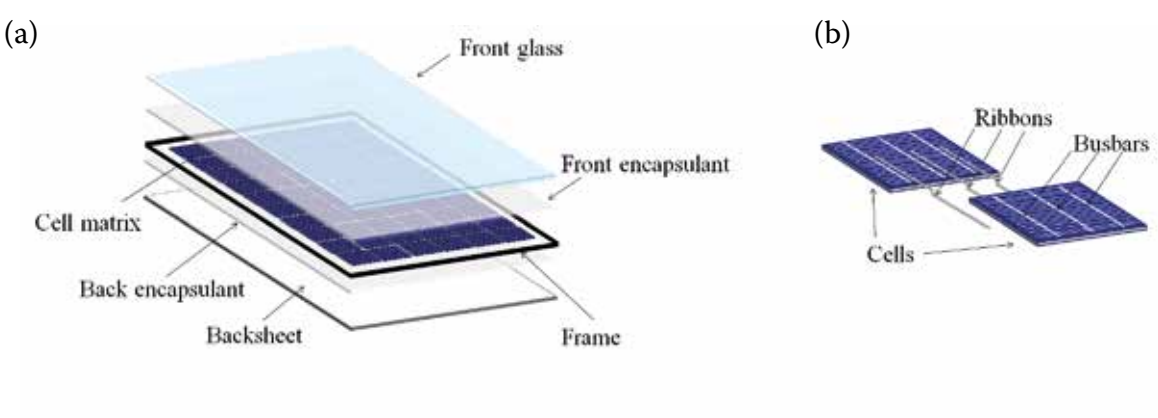

Figure 1. Standard c-Si PV modules: (a) GBS module lay-up; (b) ribbon connection technology for c-Si solar cells with BBs.

made at the cell and module levels in recent years. In addition, even if the dominance of EVA (>80% of the market share) remains currently uncontested, during the last few years (especially with the emerging cell technologies) non-EVA-based products have been proposed as an alternative encapsulant material.

The first step of the study entailed an analysis of the compatibility, in terms of lamination processability, of the most cost-effective types of encapsulant currently available on the market, with a PV module design based on a glass-glass (GG) lay-up and SmartWire Connection Technology (SWCT). The reliability of this specific module design was subsequently demonstrated.

"In terms of mechanical strength, a module design with two glasses of the same thickness is ideal."

PV module design: glass–glass lay-up and SWCT

Glass–glass lay-up

To ensure the mechanical stability of the PV modules and provide efficient protection to the cells and metallization, a GG module configuration is clearly the most appropriate solution (Fig. 3(a)). In terms of mechanical strength, a module design with two glasses of the same thickness is ideal; indeed, this symmetric configuration leads to a zero force in the photovoltaic cell, despite the external load forces (wind, snow) that can stress a PV module during its lifetime. This improved mechanical stability avoids the need for a metallic frame around the module, thus reducing the cost and, furthermore, the risk of PID. Moreover, if the polymer-based backsheet is replaced by a glass, the penetration of moisture into the module is drastically reduced, as it can only penetrate into the module from the edge area [7]. For an encapsulant with high water diffusivity, such as EVA, the typical equilibrium time needed by the water content to reach equilibrium conditions passes from days/weeks in the case of GBS, to years in the case of GG. The use of an encapsulant with a lower diffusivity and/or the use of an efficient edge sealant can further reduce the moisture ingress. This decrease in water vapour ingress has a direct positive impact on PV module reliability compared with that for a standard GBS lay-up.

Recent developments of thin, 2mm tempered glass have made GG design a more competitive solution, compared with 3 or 4mm GG modules (heavyweight) or standard GBS modules. In the case of bifacial cells, GG lay-up is clearly the best solution for exploiting the advantages of such cells in terms of energy yield [8]. In addition, instead of systems with framed modules, less-expensive mounting systems based on innovative techniques can be used

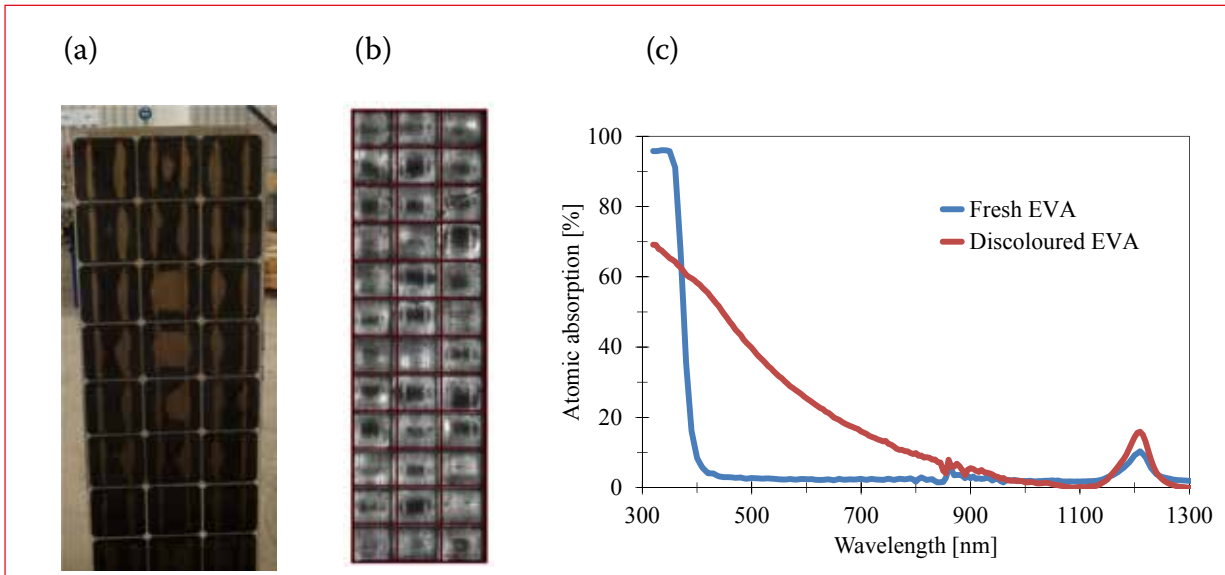

Figure 2. A solar module after 20 years' outdoor exposure on the roof of a building in Switzerland (power loss 15%): (a) delamination and yellowing; (b) electroluminescence image showing metallization corrosion; (c) absorption of the module's discoloured EVA, compared with fresh EVA.

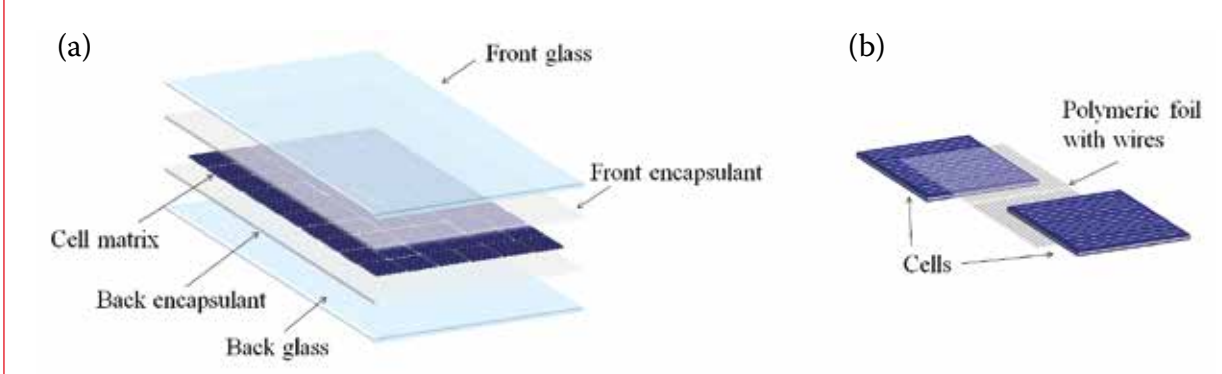

Figure 3. Novel PV module design: (a) GG module lay-up; (b) SWCT for c-Si solar cells without BBs.

[9]. The substitution of a thin glass for a thick one also increases the light transmission and speeds up the heat transfer, allowing a much shorter time for the lamination process.

SWCT

Today, high-efficiency solar cells – such as heterojunction technology (HJT), passivated emitter rear totally diffused (PERT) or interdigitated back-contact technology (IBC) – require special care, as the losses during photogenerated current transportation need to be reduced without sacrificing solar module reliability. SWCT, initially proposed by Day4 Energy [10] and now industrialized by Meyer Burger [11], is an effective alternative to standard BB and ribbon technology for realizing the highest possible benefits from these high-efficiency solar cells.

Typically, 18 copper-based wires, coated with a low-melting-point alloy, are used on both sides of the solar cell; the wires are embedded in a polymeric foil directly applied to the metallized cell (Fig. 3(b)). The soldering process takes place during the lamination process at temperatures typically below 165°C, thereby reducing the stress to the wafer. Compared with standard BBs and tinned copper ribbons, SWCT offers different advantages. The use of multiple wire connections allows the implementation of fine-line metallization on the cell (for the same ohmic loss), thereby reducing shadowing losses and economizing material costs, especially when expensive materials (such as silver paste) are used for metallization [12]. The large number of thin wires, compared with BB technology, is of even greater interest in the case of bifacial cells, for which a higher current (up to 20 to 30% more) has to be extracted, and for which metallic fingers are formed both on the front and on the back side. The cost saving is therefore higher thanks to the reduced resistive losses in the fingers, with the potential of using a low quantity of silver on both sides of the cell.

PV modules based on a module design with a 2mm-GG lay-up and SWCT were constructed using full-square 156mm × 156mm HJT bifacial cells produced by Choshu Industry Corporation [13] (nominal conversion efficiencies over 22% measured with GridTouch contacting technology developed by PASAN [14]). A maximum power of up to 311Wp_{front} (front-side illumination) resulted from module testing (Fig. 4); this value is unquestionably higher than that for standard c-Si cell PV modules. Furthermore, for installation above surfaces with good or high reflectivity, the energy yield of GG bifacial modules (kWh/kWp_{front}) is up to 15–30% higher than the energy yield of standard GBS monofacial modules (kWh/kWp), resulting in a significant reduction in the levelized cost of electricity (LCOE) [8].

> "The energy yield of GG bifacial modules is up to 15–30% higher than the energy yield of standard GBS monofacial modules."

Encapsulants overview

The rapid development of the PV market during the last few years has caused a substantial expansion of the encapsulant material market for photovoltaic applications [15–17].

For GG lamination, **polyvinyl butyral (PVB)** is a well-known thermoplastic (non-cross-linked) encapsulant. It has been used for a long time in architecture for safety-glass laminates, as well as in the PV industry for building-integrated photovoltaics (BIPV) and for thin-film technology with a GG configuration. One disadvantage of PVB is that it is very sensitive to hydrolysis because of high water uptake.

The durability of EVA is mainly influenced by the additive elements but has been considerably improved in recent years. Many solutions have been presented with regard to the degradation problem of yellowing, but other degradation reactions (acetic acid production) still remain for this type of encapsulant. The use of cross-linking additives in EVA encapsulants also creates issues in terms of both module processing time and material storage.

Liquid silicone demonstrates excellent resistance to oxygen, ozone and UV light, a wide temperature stability range, excellent transparency in the UV-visible range and low moisture uptake. Although very promising as an encapsulant material, silicone is only rarely used (e.g. extraterrestrial applications) owing to its high price and the need for special processing machines.

Encapsulants based on a

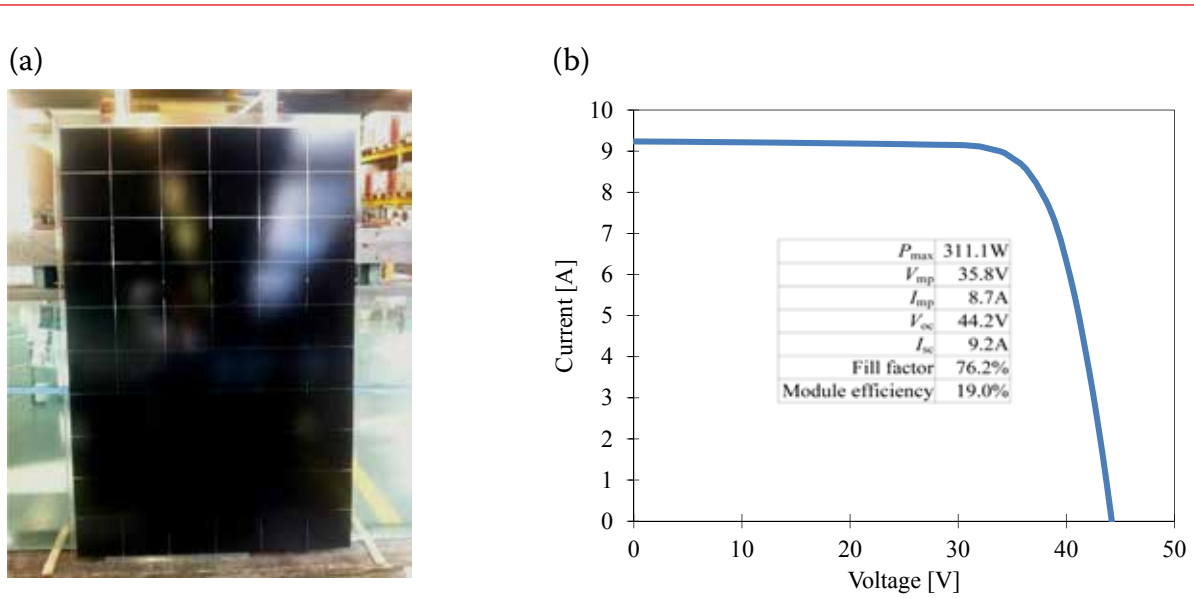

Figure 4. (a) 2mm-GG PV module with SWCT and HJT bifacial cells (CIC) produced by Meyer Burger; (b) measured *I–V* curve at standard test conditions (STC), using a PASAN sun simulator with a black housing to avoid parasitic reflection on the back side of the module.

thermoplastic polyolefin (**TPO**) or **thermoplastic elastomer** (**TPE**) are now starting to enter the market because of their high electrical resistivity and their hydrolysis resistance. These properties make TPO encapsulants an interesting candidate for long-lasting PV modules.

Thermoplastic silicone elastomers (**TPSEs**) combine silicone performance and thermoplastic processability. The fast curing and the additive-free physical cross-linking make TPSEs suitable for continuous lamination processing.

Belonging to the category of thermoplastic materials, **ionomers** represent a different class of photovoltaic encapsulant, demonstrating good UV stability. No formation of acetic acid has been observed during weathering and a much longer shelf life is achieved, but the production cost is very high.

Compared with standard PV module design based on GBS module lay-up and BB ribbon connection technology, the new PV module design based on a 2mm-GG lamination scheme with SWCT and new high-efficiency solar cells implies a paradigm shift in the encapsulant requirements. Even more than the technical requirements, the main driving force that governs the selection of the encapsulant material suitable for this PV module design is the intense and ever-increasing pressure to reduce module costs. From this point of view, only EVA, PVB and TPO demonstrate a cost that is affordable when considering a promising encapsulant for the PV module design based on 2mm-GG with SWCT for high-efficiency solar cells.

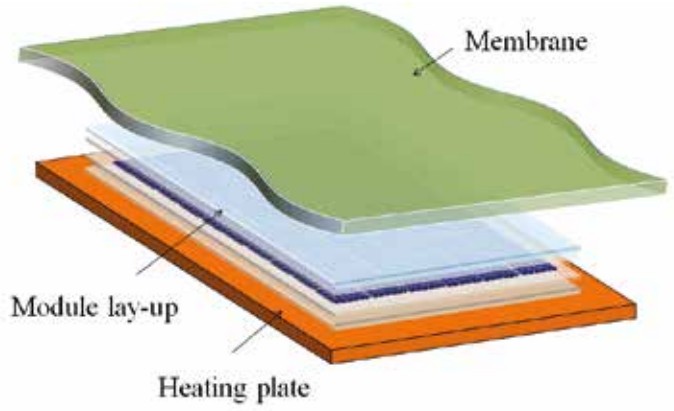

Figure 5. Schematic representation of a standard vacuum-membrane laminator.

Encapsulant	Producer Note
PVB	Outstanding UV transparency
EVA1	Fast cure EVA
EVA2	Highly light transmitting encapsulant
TPO1	Slightly cross-linking TPO
TPO2	Non-cross-linking TPO

Table 1. Selection of the most cost-effective encapsulants tested in terms of compatibility with the lamination process of the novel module design.

Lamination process for the new module design

The lamination of PV modules is most frequently carried out using a vacuum-membrane laminator with a single heating plate (Fig. 5) and a typical process based on three main steps [18].

In the first step, after the module lay-up has been loaded into the laminator, air and other volatile organic compounds (VOCs) are removed by vacuum while the module lay-up is heated until the encapsulant softening

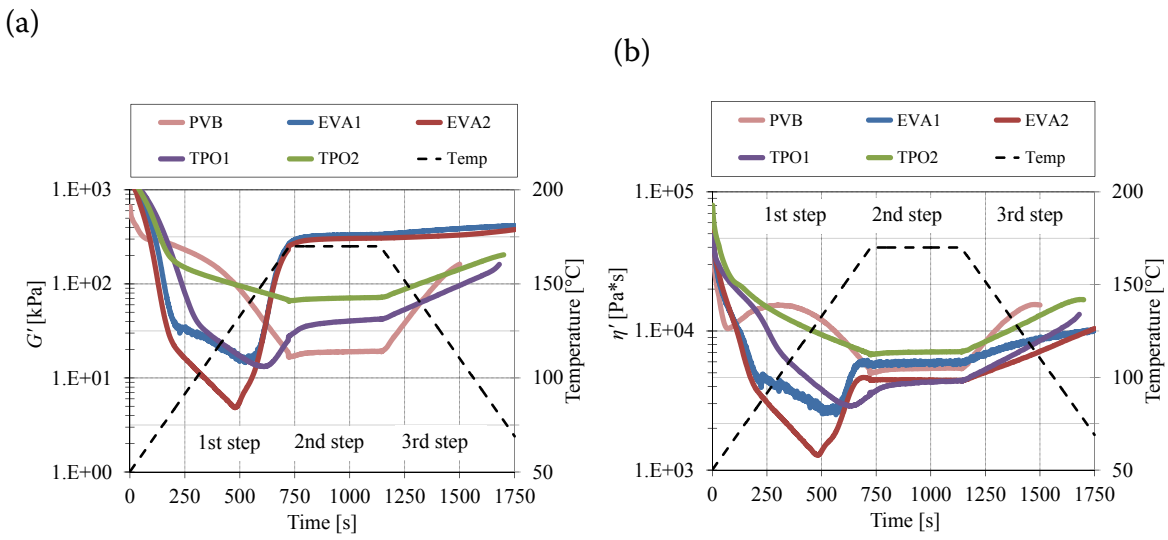

Figure 6. DMA results for the encapsulants in Table 1 (oscillatory frequency = 1Hz; strain = 10%; pressure = 2.5bar) as a function of a given temperature profile: (a) shear modulus (*G'*); (b) viscosity (*η'*).

point is reached. Under the effect of the heat, the VOCs are mainly released from the encapsulant as a result of the chemical reactions of their additives (including impurities). If VOCs are not properly removed during this first step of the lamination process, they could lead to bubbles in the final module [19]. In the second step, the flexible membrane is pressed on the module lay-up to ensure an optimal adhesion between the encapsulant and the other layers of the module lay-up. Finally a controlled cooling step terminates the induced chemical reactions and makes the PV module ready for the next processing steps.

Encapsulants (such as cross-linked EVA) with a large number of additives that cause a significant number of VOCs are not well suited to the lamination of PV modules based on 2mm-GG lay-up and SWCT. In order to promote the interconnection process during the lamination, while keeping the polymeric foil with the wires in good contact with the cells as the encapsulant melts, a slight pressure must be applied during the first vacuum phase. Pressing the module lay-up onto the heating plate results in an improved heat transfer (from the heating plate to the module lay-up), which speeds up the chemical reactions and hence the release of VOCs. In this phase, the applied pressure obstructs the removal of air and VOCs, consequently increasing the likelihood of bubble formation.

With regard to GBS, the lamination of a 2mm-GG module presents more critical aspects because of the stiffness of the glasses. It is well known that encapsulants are viscoelastic, thus exhibiting both elastic (spring-like) and viscous (dashpot-like) behaviour. Knowledge of how the elastic modulus and viscosity of an encapsulant under pressure vary with the temperature helps in choosing which encapsulant is more suitable for the lamination of a 2mm-GG PV module.

The complex shear modulus ($G^* = G' + iG''$) and the complex viscosity ($\eta^* = \eta' - i\eta''$) for a polymer material can be calculated using dynamic mechanical analysis (DMA); here, the quantities G' and η'' are a measure of the energy storage portion, while G'' and η' are a measure of the energy loss portion [20]. For a selection of the most cost-effective encapsulants (Table 1), Fig. 6 shows the measured values of G' and η' as a function of a specific temperature profile resembling the temperature variation during a standard lamination process.

The PVB encapsulant demonstrates a full thermoplastic behaviour, with both G' and η' following the temperature profile.

For the two EVA encapsulants, G' and η' quickly reach a minimum at approximately 125°C (melted encapsulant); they then increase significantly, indicating the initiation of the cross-linking process. The formation of a cross-linked network implies an elastic-like material behaviour (high value of G') that is maintained when the temperature goes down.

The two TPO encapsulants yield significantly different behaviours. The G' and η' profiles of TPO1 resemble those of the two EVA encapsulants, with cross-linking around 150°C; however, a reduced elastic behaviour (low value of G') during the second step of the lamination process is observed. In the case of the TPO2 encapsulant, G' and η' are instead closer to the thermoplastic trend of PVB, but with a higher value of G' (more elastic-like behaviour) during the second step of the lamination process.

In a 2mm-GG configuration, the flowing of the encapsulant into the space between the cells is strongly related to its viscous properties during the lamination process. Encapsulants with a high viscosity (in the first step of the lamination process), such as PVB and TPO2, need more time to flow and fill the gaps between the cells. Any remaining unlaminated patches (incomplete melting of the encapsulant) between the cells might then lead to a delamination issue. To avoid this issue, process times of over 30–40 minutes are necessary with these encapsulants.

On the other hand, the use of encapsulants that exhibit low viscosity and low elastic behaviour (e.g. TPO1) may cause, in a 2mm-GG configuration, other issues relating to excessive compression of the edges of the glasses. During the lamination process, the encapsulant may flow out as the membrane bends down the edges of the top glass (Fig. 7(a)). The difference in GG laminate thickness measured at the centre of the first cell close to the edge (d_1) and at the glass edges (d_2) can also be up to 0.8–1.0mm after the lamination process (Fig. 7(b)). The compression of the edges causes glass breakage when the module is stressed during thermal cycles. Using a frame of the same thickness as the GG lay-up or taping the edges of the module before lamination helps in reducing this effect but complicates the lamination process.

To avoid the issue of unlaminated patches between the cells, as well as the issue of edge compression, without the inconveniences of long lamination processes and/or using taping or a frame, a laminator with a symmetrical structure (two heating plates without any vacuum membrane) like the one recently developed by Meyer Burger can be employed for the lamination of a PV module with a 2mm-GG lay-up and SWCT (Fig. 8). The advantages of such a laminator concept lie mainly in the fact that with two heating plates, the PV module lay-up is heated symmetrically from the top and the bottom sides, resulting in a faster heat transfer towards the encapsulant. The

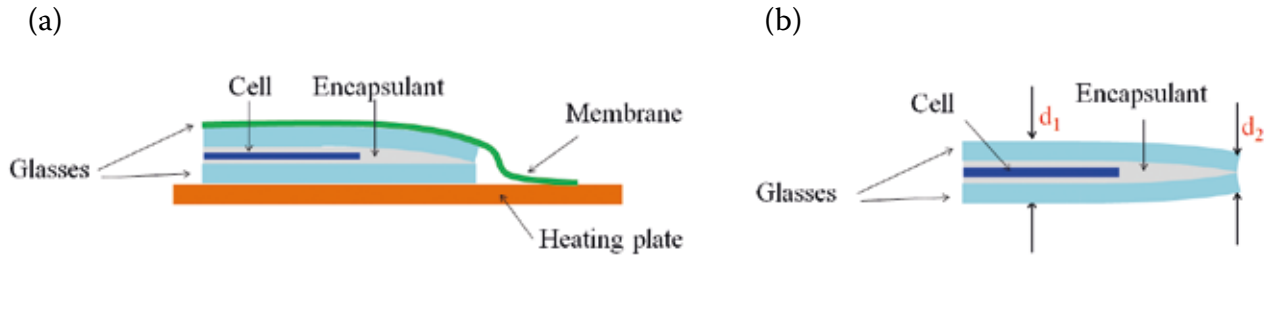

Figure 7. (a) Edge compression in 2mm-GG laminate for encapsulants with low viscosity and using a vacuum-membrane laminator; (b) difference in thickness of the 2mm-GG laminate at the centre of the first cell close to the edge and at the glass edges.

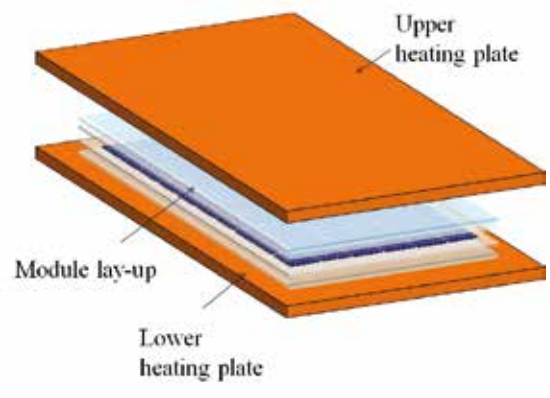

Figure 8. Schematic representation of a symmetrical laminator for GG PV module production.

Encapsulant	WVTR [g/(m²·24h)]	Water absorption [%]
PVB	>25	~0.5
EVA	15–25	~0.3–0.5
TPO	<5	<0.1

Table 2. Typical WVTR and water absorption for different types of encapsulant.

	GG-TPO	GG-EVA	GBS-EVA
ΔP_{max}	–0.4%	–19.5%	–42.0%
ΔI_{sc}	–0.7%	–1.5%	–25.0%
ΔV_{oc}	0.3%	–1.3%	0.0%
ΔFF	0.0%	–16.8%	–17%

Table 3. DH test results for a GG module (SWCT) laminated with TPO, compared with GG and GBS modules (ribbon connection technology) laminated with EVA.

encapsulant flows rapidly between the cells, and a GG PV module without unlaminated patches can be obtained within a short process time for high-viscosity encapsulants as well.

"To avoid the issue of unlaminated patches between the cells, as well as the issue of edge compression, a laminator with a symmetrical structure can be employed."

A process time under eight minutes in a single chamber GG laminator has been obtained by Meyer Burger for a 2mm-GG PV module based on SWCT using TPO1. Moreover, because the pressure is applied by the two metallic heating plates, the edge compression, without using any frame or tape, is kept lower (in the range 0.4–0.6mm) compared with the values observed in a membrane laminator (up to 1mm). The combination of such a laminator with a non-cross-linked (or only slightly cross-linked) TPO is therefore the appropriate solution for the lamination of PV modules based on a 2mm-GG lay-up and SWCT.

The investment costs (normalized per generated MW after seven years of operation) of 2mm-GG PV modules with a symmetrical laminator have been estimated to be up to 30% lower than the costs of using a standard vacuum-membrane laminator, and will be competitive with the investment costs of standard GBS modules using a standard laminator.

Reliability of GG module design

As stated earlier, an important factor influencing a PV module's reliability is the moisture ingress into the module. Even if humidity ingress is drastically reduced in a GG configuration, encapsulants with low water diffusivity and absorption are preferable for long-lasting PV modules. Water vapour transmission rate (WVTR) and water absorption values for the most cost-effective encapsulants available on the market are presented in Table 2 [21–24].

From the data listed in Table 2, for improving module reliability TPO encapsulants are therefore the more promising materials compared with EVA and PVB, as they demonstrate low values for both WVTR and water absorption. In particular, low values of water absorption are essential for preventing corrosion mechanisms that can be activated by the presence of additives (including impurities) in the encapsulant [25]. For the same reason, non-cross-linked (or only slightly cross-linked) TPO is also more promising than highly cross-linked EVA.

In damp-heat conditions (DH: 85°C, 85% RH), GG PV modules (incorporating HJT cells) with SWCT and a TPO encapsulant (TPO1 in Table 1) endure 7000h (seven times the IEC test standard) without noticeable power degradation. In contrast, PV modules (standard ribbon connection technology) laminated with EVA encapsulant (EVA1 in Table 1) for GG and GBS lay-ups exhibit power losses of 19.5% and 40%, respectively, after the same length of time in DH conditions (Table 3).

An electroluminescence analysis revealed degradation due to moisture ingress and corrosion of the cells for the module with the EVA encapsulant, while no degradation issues were observed for the module with the TPO encapsulant (Fig. 9). The lower power loss of the GG module with EVA (GG-EVA) compared with that of the GBS-EVA module is proof of the improvements realized by replacing the polymer-based insulating backsheet with a glass. However, it is only with the use of TPO encapsulants with low water absorption and no (or few) cross-linking additives that very long-lasting PV modules can be produced.

GG PV modules (incorporating HJT cells) with SWCT and TPO encapsulant (TPO1 in Table 1) also achieve successful results in extended thermal-cycling tests (TC: –40°C/+85°C), with a power output degradation of only 2.5% after 800 cycles (eight times the IEC standard) (see Table 4).

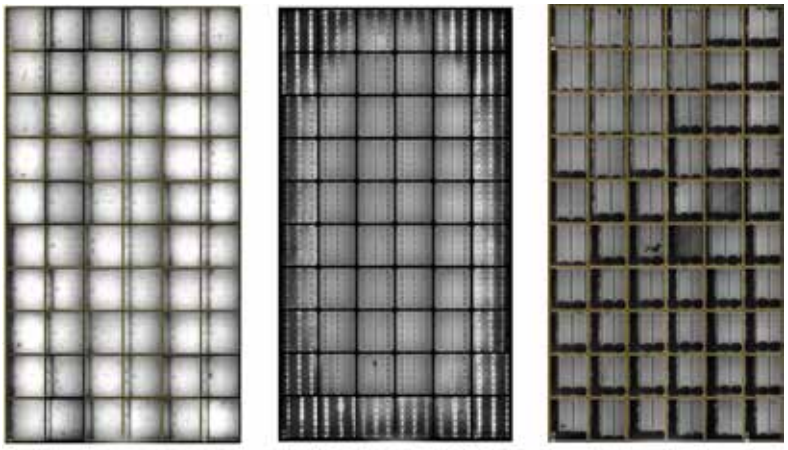

Figure 9. Electroluminescence analysis after DH: (a) GG module (SWCT) laminated with TPO; (b) GG module with ribbon connection technology laminated with EVA; (c) GBS module with ribbon connection technology laminated with EVA.

	TC200	TC600	TC800
ΔP_{max}	–0.4%	–1.5%	–2.6%
ΔI_{sc}	–0.4%	0.0%	0.7%
ΔV_{oc}	0.1%	0.5%	0.8%
ΔFF	–0.5%	–2.2%	–3.4%

Table 4. Thermal-cycling test results for a GG module (SWCT) with a TPO encapsulant.

The good results obtained for extended DH and TC testing substantiate the high reliability of PV modules based on a module design with GG and SWCT when a slightly cross-linked TPO encapsulant (TPO1 in Table 1) is used. Moreover, the lower volume resistivity of TPO encapsulants ($\rho v = 10^{14}$–$10^{17}\Omega cm$, compared with $\rho v = 10^{14}\Omega cm$ for EVA) also guarantees lower PID [26,27]. The cross-linking additionally offers an increased resistance to long-term creeping of the encapsulant at high service temperatures.

"In combination with bifacial HJT cells, the novel module design enables PV modules with a maximum power of up to 311Wp to be obtained."

Conclusions

A novel high-efficiency and long-lasting PV module design based on a thin, 2mm-GG encapsulation scheme and SWCT has been presented. In combination with bifacial HJT cells, the novel module design enables PV modules with a maximum power of up to 311Wp to be obtained. As well as high power, the bifaciality of such a module would produce a 10–30% higher energy yield.

Non-cross-linked (or slightly cross-linked) TPO encapsulants yield the best results (no bubbles, limited edge compression and a short process time) with regard to processability of the GG module design when a symmetrical laminator is used. Thanks to the high-reliability properties of TPO encapsulants (low water absorption and small number of additives), more-reliable PV modules passing extended IEC tests (7000h in DH and 800 cycles in TC) can be obtained.

Acknowledgements

The authors thank the Swiss Commission for Technology and Innovation (14567.1 PFIW-IW project), the Swiss Federal Office of Energy (Swiss Inno-HJT project), the European Union's Seventh Programme (608498 HERCULES project) and Choshu Industry Corporation for their support.

References

[1] IEA-PVPS 2014, "Review of failures of PV modules", Report T13-01.
[2] Chaberlin, C.E. et al. 2011, "Comparison of PV module performance before and after 11 and 20 years of filed exposure", *Proc. 37th IEEE PVSC*, Seattle, Washington, USA.
[3] Jordan, D.C. et al. 2013, "Photovoltaic degradation rates – An analytical review", *Prog. Photovolt.: Res. Appl.*, Vol. 21, No. 1, pp 12–29.
[4] Kempe, M.D. et al. 2007, "Acetic acid production and glass transition concerns with ethylene-vinyl acetate used in photovoltaic devices", *Solar Energy Mater. & Solar Cells*, Vol. 91, No. 4, pp. 315–329.
[5] Ketola, B. et al. 2011, "Degradation mechanism investigation of extended damp heat aged PV modules", *Proc. 26th EU PVSEC*, Hamburg, Germany, pp. 3523–3528
[6] Berghold, J. et al. 2010, "Potential induced degradation of solar cells and panels", *Proc. 25th EU PVSEC*, Valencia, Spain, pp. 3753–3759.
[7] Kempe, M.D. 2006, "Modeling of rates of moistures ingress into photovoltaic modules", *Solar Energy Mater. & Solar Cells*, Vol. 90, pp. 2720–2738.
[8] Kopecek, R. et al. 2014, "Bifaciality: One small step for technology, one giant leap for kWh cost reduction", *Photovoltaics International*, 26th edn, pp. 32–45.
[9] Schletter 2012, OptiBond Product Sheet [available online at http://www.schletter.de/files/addons/docman/solarmontage/produktblaetter/OptiBond_-_product_sheet_V5_I400051GB.pdf]
[10] Schneider, A. et al. 2006, "Solar cell efficiency improvement by new metallization techniques – The Day4 electrode concept", *Proc. 4th IEEE WCPEC*, Waikoloa, Hawaii, USA, pp. 1095–1098.
[11] Söderström, T. et al. 2013, "Smart Wire Connection Technology", *Proc. 28th EU PVSEC*, Paris, France, pp. 495–499.
[12] Faes, A. et al. 2014, "SmartWire solar cell interconnection technology", *Proc. 29th EU PVSEC*, Amsterdam, The Netherlands, pp. 2555–2561.
[13] Kobayashi, E. et al. 2014, "Rear-emitter silicon heterojunction solar cells cerium oxide-doped indium oxide", *Proc. 29th EU PVSEC*, Amsterdam, The Netherlands, pp. 472–474
[14] Bassi, N. et al. 2014, GRID^{TOUCH}: Innovative solutions for accurate

IV measurements of busbarless cells in production and laboratory environments", *Proc. 29th EU PVSEC*, Amsterdam, The Netherlands, pp. 1180–1185
[15] Peike, C. et al. 2013, "Overview of PV module encapsulation materials", *Photovoltaics International*, 19th edn, pp. 85–92.
[16] Oreski, G. 2014, "Encapsulant materials and degradation effects – Requirements for encapsulants, new materials, research trends", IEA Task 13 Open Workshop, Freiburg, Germany.
[17] Kempe, M.D. et al. 2010, "Types of encapsulant materials and physical differences between them", NREL Presentation [available online at http://www1.eere.energy.gov/solar/pdfs/pvrw2010_kempe.pdf].
[18] Lange, F.M. et al. 2011, "The lamination of (multi)crystalline and thin film based photovoltaic modules", *Prog. Photovolt.: Res. Appl.*, Vol. 19, No. 2, pp. 127–133.
[19] Perret-Aebi, L.-E. et al. 2010, "Insights on EVA lamination process: Where do the bubbles come from?", *Proc. 25th EU PVSEC*, Valencia, Spain, pp. 4036–4038.
[20] Menard, K.P. 2008, *Dynamic Mechanical Analysis: A Practical Introduction*. Boca Raton, FL, USA: Taylor & Francis.
[21] Velderrain, M. 2012, "Designing low permeability, optical-grade silicone systems: Guidelines for choosing a silicone based on transmission rates for barrier applications", *Proc. SPIE* (Vol. 8280: Advances in Display Technologies II), San Francisco, California, USA.
[22] Ketola, B. et al. 2008, "Silicones for photovoltaic encapsulation", *Proc. 23rd EU PVSEC*, Valencia, Spain, pp. 2969–2973.
[23] Hülsmann, P. et al. 2014, "Temperature-dependent water vapour and oxygen permeation through different polymeric materials used in photovoltaic-modules", *Prog. Photovolt.: Res. Appl.*, Vol. 22, pp. 415–421.
[24] Swonke, T. et al. 2009, "Impact of moisture on PV module encapsulants", *Proc. SPIE* (Vol. 7412: Reliability of Photovoltaic Cells, Modules, Components, and Systems II), San Diego, California, USA.
[25] Ketola, B. et al., "The role of encapsulant moisture permeability in the durability of solar photovoltaic modules", Dow Corning Presentation [available online at http://www.dowcorning.com/content/publishedlit/The_Role_of_Moisture.pdf]
[26] Nanjundiah, K. et al. 2012, "Improved performance encapsulation film based on polyolefin", *Proc. 27th EU PVSEC*, Frankfurt, Germany, pp. 3384–3387.
[27] Liciotti, C. et al. 2014, "Temperature dependence of encapsulant volumetric resistivity and influence on potential induced degradation of c-Si modules", *Proc. 29th EU PVSEC*, Amsterdam, The Netherlands, pp. 3093–3099

About the Authors

Gianluca Cattaneo obtained his M.Sc. in electronic engineering in 2004 from the Polytechnic of Milan and joined the IMT PV-Lab of EPFL in Neuchâtel in 2012. Since 2014 he has been working in the modules and systems sector at the CSEM PV-Center.

Antonin Faes received a master's in material science from the Swiss Federal Institute of Technology Lausanne (EPFL) in 2005, and then investigated solid oxide fuel cells, for which he received his Ph.D. He joined the CSEM PV-Center in 2012, where he is responsible for the metallization and interconnection of c-Si cells.

Heng-Yu Li received his Ph.D. from EPFL in 2013. Since 2009 he has been working on the encapsulation process and reliability of PV modules at IMT PV-Lab at EPFL. In 2014 he joined the CSEM PV-Center, where he focuses on developing reliable PV modules for various applications, including BIPV.

Federico Galliano obtained his Ph.D. from the University of Florence in 2001. Since 2013 he has been working in the modules and systems sector at the CSEM PV-Center, with a main focus on PV module reliability and building integration.

Maria Gragert received her Diploma in chemistry (with Honours) from the Martin-Luther university Halle-Wittenberg in 2010, and her Ph.D. from Imperial College London in polymerization catalysis. Since 2014 she has been working in the R&D department of Meyer Burger AG, focusing on process optimization for module lamination.

Yu Yao received her Ph.D. from the University of New South Wales (UNSW), with a thesis topic involving crystalline silicon solar cells. She joined Meyer Burger AG in 2014 as an R&D project manager, where she focuses on the development of SmartWire Connection Technology.

Rainer Grischke graduated in 1999 from the University of Kassel, Germany, in electrical engineering, with a main focus on renewable energy. Since 2014 he has been with Meyer Burger AG as a member of the R&D team working on module improvements relating to the novel SmartWire module concept.

Thomas Söderström received a master's in 2005 from EPFL and a Ph.D. in 2009 from the University of Neuchâtel (UNINE, Switzerland), with a focus on thin-film silicon solar cells. He is currently head of the transfer process and innovation module department at Meyer Burger AG, working on the development and industrialization of heterojunction SmartWire bifacial module technology.

Matthieu Despeisse received his degree in electrical engineering in 2002 from INSA in Lyon, and a Ph.D. in 2006 for his work on amorphous silicon radiation sensors vertically integrated onto integrated circuits. Since 2013 he has led research activities on crystalline silicon solar cells development at CSEM PV-Center, with a particular focus on silicon heterojunction technology, passivation contacts and metallization.

Christophe Ballif received his M.Sc. and Ph.D. degrees in physics from EPFL in 1994 and 1998, focusing on novel photovoltaic materials. He is currently Director of the IMT PV-Lab at EPFL and, since 2013, has also been Director of the CSEM-PV-Center. His research interests include thin-film silicon, high-efficiency heterojunction crystalline cells, module technology, contributing to technology transfer, and industrialization of novel devices.

Laure-Emmanuelle Perret-Aebi obtained her Ph.D. in chemistry in 2004 from the University of Fribourg, Switzerland. She is currently section head of the modules and systems sector at the CSEM PV-Center, where her main research activities focus on the development of innovative and highly reliable PV modules for various applications, such as building, mobile and ground-based power plants.

Enquiries

Gianluca Cattaneo
CSEM, PV-Center
Jaquet-Droz 1
2000 Neuchâtel
Switzerland

Tel: +41 32 720 5553
Fax: +41 32 718 3201
Email: gianluca.cattaneo@csem.ch