Double-glass PV modules with silicone encapsulation

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ABSTRACT

Double-glass PV modules are emerging as a technology which can deliver excellent performance and excellent durability at a competitive cost. In this paper a glass–glass module technology that uses liquid silicone encapsulation is described. The combination of the glass–glass structure and silicone is shown to lead to exceptional durability. The concept enables safe module operation at a system voltage of 1,500V, as well as innovative, low-cost module mounting through pad bonding.

Introduction

Recently several double-glass (also called glass–glass or dual-glass modules) c-Si PV modules have been launched on the market, many of them by major PV manufacturers. These modules use a sheet of tempered glass at the rear of the module instead of the conventional polymer-based backsheet. There are several reasons why this structure is appealing. First, glass is completely impermeable to moisture and therefore degradation caused by water ingress is expected to be much slower than for a conventional glass–backsheet structure with the same encapsulant. Moreover, a glass–glass laminate is mechanically much more robust than a glass–backsheet laminate, even if thin 2mm glass is used. This is because the double sheet of glass provides higher rigidity while the cells are placed in the 'neutral plane' of the laminate and therefore experience no compression or tension when the structure is bent; this greatly reduces fatigue stresses in the tabbing. The possibility of using thin glass for the front cover also enables a small efficiency increase thanks to the higher light transmittance relative to the thick front cover glass. Finally, a glass–glass structure enables a frameless installation and/or the implementation of rail or pad bonding instead of conventional module affixation.

Even more than for conventional modules, the bill of materials is critical for double-glass modules. In particular, the choice of encapsulant has a large impact on the module manufacturing process as well as on performance and reliability [1]. Various encapsulant materials can be considered. Polyvinyl butyral (PVB) has been used for a long time for glass–glass PV modules, particularly for thin-film modules. For various reasons (it entails a longer, more complicated process, and comparatively high water uptake), this is not the preferred material for modern crystalline Si double-glass modules.

Several manufacturers have chosen to use the material that has become standard in the manufacturing of conventional glass–backsheet modules, namely ethylene vinyl acetate (EVA). This is challenging, as volatile organic compounds are generated as by-products of the peroxide cure initiation reactions and need to be fully evacuated before cure completion – otherwise voids are formed [1]. This is not easy to achieve for glass–glass structures, and very careful process tuning is necessary. Nevertheless, several EVA-encapsulated double-glass modules are now commercially available.

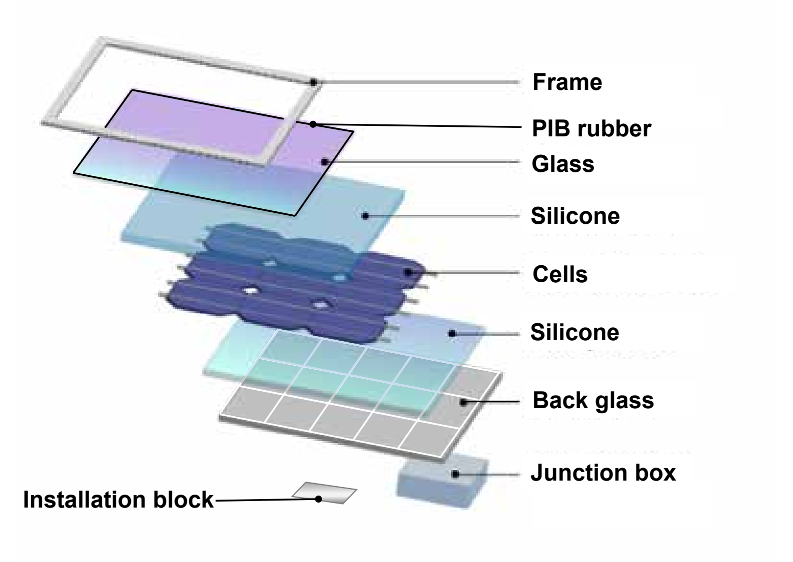


Figure 1. Schematic structure of BYD's double-glass module.

> "Silicone as an encapsulant material is extremely stable under thermal and UV stress."

Another family of materials that has been considered is thermoplastic or slightly cross-linking polyolefins (TPO) [2]. Finally, one can use silicone as an encapsulant material; this is known to be extremely stable under thermal and UV stress. The use of a liquid encapsulant, such as silicone, also reduces cell damage caused during the placement of the second piece of glass.

Early PV modules were often encapsulated with silicone, and have demonstrated outstanding stability in the field, with degradation rates over 20 to 30 years that are much lower than the typical degradation rates for EVA-encapsulated modules [3–5]. The silicone materials used at the time, however, were products that had been developed for electronics, and the manufacturing processes were not adapted to PV needs. A few years ago, renewed interest led to the development of dedicated silicones for modern PV modules [6,7], resulting in the recent launch of a new optimized silicone encapsulant [8]. Aiming for an extremely durable and reliable module, and on the basis of an assessment of the various encapsulation options for double-glass modules, it was decided to implement this new silicone encapsulation technology in BYD's double-glass PV module product. This paper describes the module concept and design, discusses the manufacturing implementation, and highlights module performance and very recent developments.

Module concept

The structure of the BYD module is shown in Fig. 1. As in conventional modules, it consists of several layers laminated together, with the solar cell matrix in the centre; however, there are some major differences.

The rear outer layer is not a conventional polymer backsheet, but a sheet of toughened glass, providing an excellent barrier against water vapour and electrical breakdown protection. In order to capture the maximum possible amount of light, the glass is locally coated with a white reflective layer, which is applied in a grid pattern and is aligned with the area between the cells in the final module. As mentioned earlier, a silicone PV encapsulant was used instead of conventional EVA – this aspect is covered in more detail in the next section.

In order to prevent water vapour ingress through the edges of the laminate, a polyisobutylene (PIB) rubber seal is applied along the perimeter. This material demonstrates extremely low water vapour transport rate (< 0.2mg/m^2/day) and extremely high volume resistivity ($\sim 10^{16}\Omega\cdot$cm). The combination of this rubber seal with the rear glass sheet and the silicone encapsulation leads to exceptional environmental and electrical protection of the module.

The double-glass structure makes the module quite rigid compared with

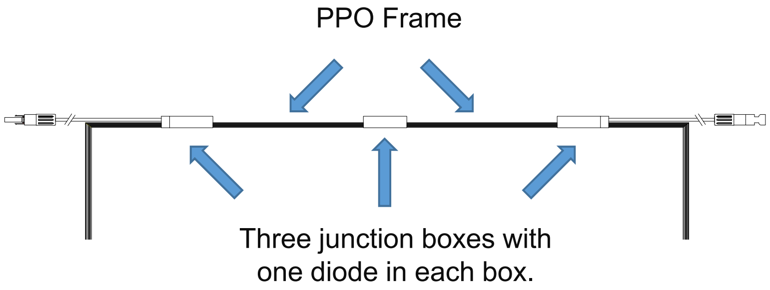


Figure 2. Detail of BYD's double-glass PV module design, highlighting the frame and the edge junction boxes.

Figure 3. Example of a PV system using BYD's double-glass modules.

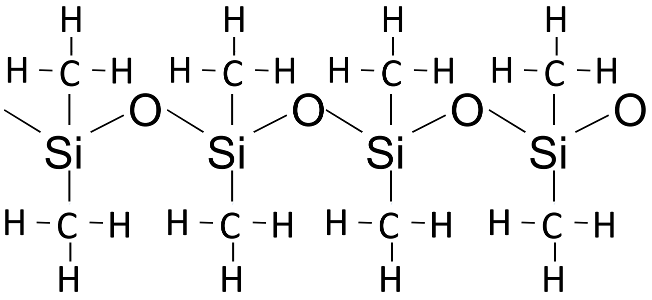


Figure 4. Chemical structure of polydimethylsiloxane silicone.

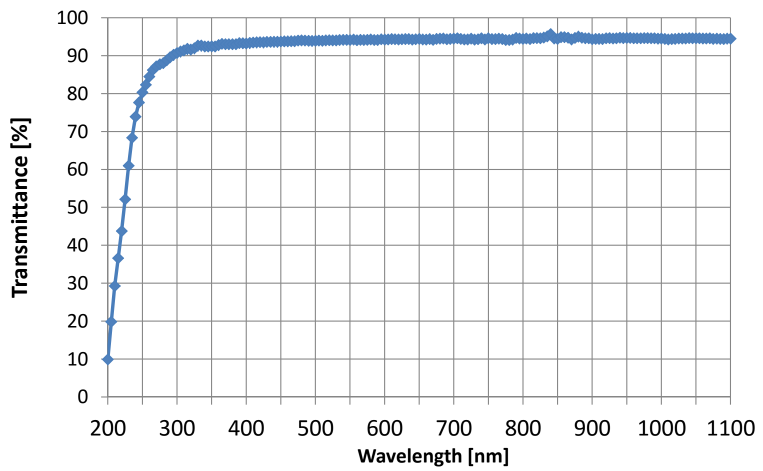


Figure 5. Transmittance of PV-6212 as a function of wavelength.

standard laminates. As a result, a conventional aluminium frame is not necessary; instead, a light frame made of polyphenylene oxide (PPO) polymer, a high-temperature thermoplastic, is used to protect the glass edges from impact during transport. Because the frame is non-conductive, it does not need to (and cannot) be grounded. The whole front surface of the module is electrically floating.

With regard to the junction box, the solution chosen consists of three separate edge junction boxes, each containing one bypass diode, instead of one central junction box containing three bypass diodes (see Fig. 2). This arrangement has several advantages. The individual junction boxes can be quite narrow and therefore maintain the sleek appearance of the module. Moreover, there is no need to be make holes in the rear glass sheet. Finally, the resistance losses are lower because of shorter cables and bussing tapes.

To mount the module onto its support, a strong metal fixture is attached to the laminate. These rectangular pieces of stainless steel, referred to as *installation blocks*, are glued directly onto the rear glass sheet using structural silicone adhesive. The technology to bond glass to structural elements in order to create structures that can withstand large wind loads is commonly practised in the construction industry and benefits from decades of experience.

The installation blocks are designed and placed on the laminate in such a way that they can be bolted onto two brackets with a U-shaped cross section. Each pair of brackets will typically carry several modules, the number of which depends on the PV system design (Fig. 3). This module concept enables flexibility in system design as well as easy installation, with a low risk of module breakage, compared with the clamping systems that are typically used for frameless modules. Mechanical load tests with a module ‘hanging from’ or ‘lying on’ two brackets showed that the modules

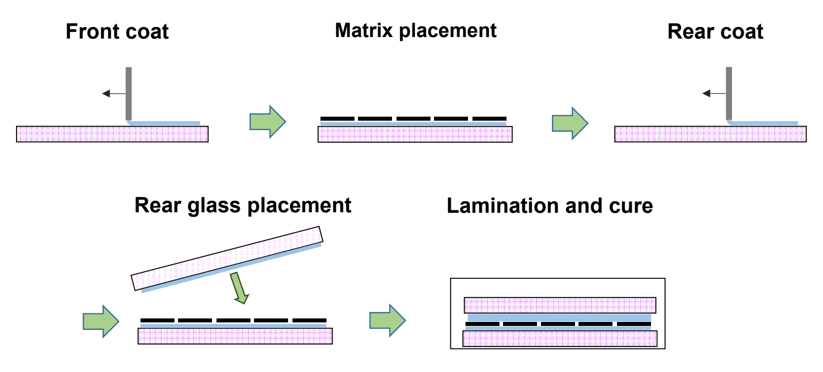


Figure 6. Encapsulation process using PV-6212 silicone encapsulant for glass–glass modules.

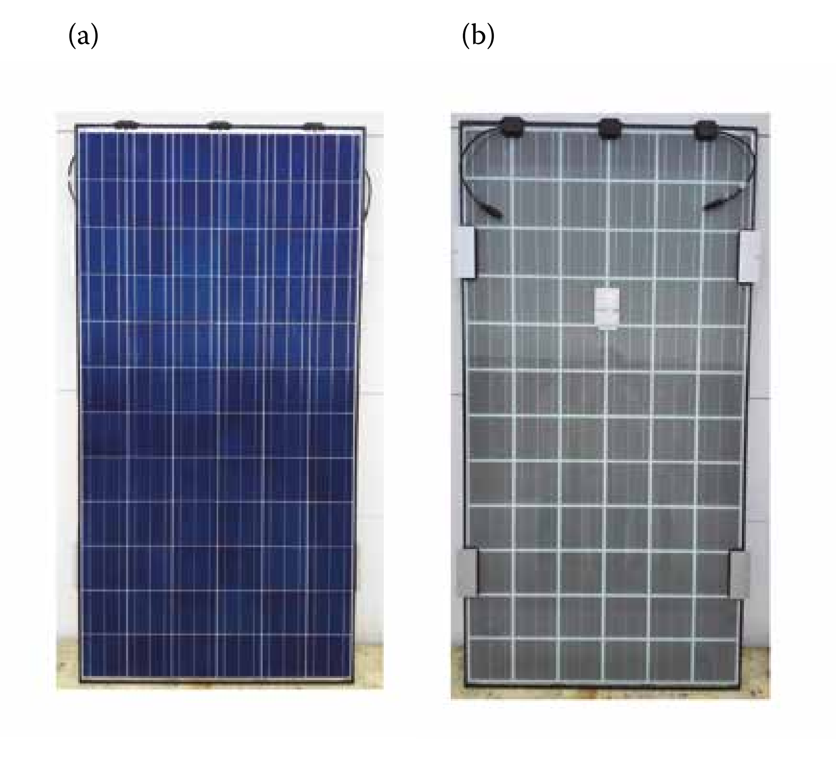


Figure 7. Front (a) and rear (b) of a fabricated BYD double-glass module.

remained intact during a wind load of 2,400Pa and a snow load of 5,400Pa, without any cracking of the cells or decrease in performance.

Silicone encapsulation

The silicone encapsulant material selected for this work was *Dow Corning*® PV-6212 Cell Encapsulant. In contrast to most commercial PV encapsulants, this material is supplied as a liquid, not as a foil. It is dispensed in the liquid form and is cured into a solid by cross-linking during lamination. PV-6212 is a polydimethylsiloxane (PDMS), consisting of molecules with a 'Si-O-Si-O…' backbone and two CH_3 groups on each Si atom (see Fig. 4), that uses an addition curing system; as a result, there is no by-product of the cross-linking reaction. PV-6212 is provided in two parts which need to be mixed just before application. The curing process results in a firm but fairly soft rubber (shore A hardness 11.5); this provides protection but still allows some movement of the encapsulated pieces, which is important for reliability in thermal cycling testing.

The Si–O bond in the silicone backbone is much stronger than the C–C bond in the backbones of organic polymers (such as EVA), with a bond energy of 452KJ/mol vs. 346KJ/mol; this makes the material intrinsically more stable. Moreover, cured PV-6212 has a high transparency, including over the UV range, in which conventional encapsulants have reduced transmittance (Fig. 5). This is particularly important for new solar cell technologies which demonstrate improved response at short wavelengths. The transparency in the UV range also makes the silicone inherently more resistant to hardness and colour changes caused by UV degradation.

The encapsulation process is shown schematically in Fig. 6; it begins with the dispensing of PV-6212 onto the first glass panel. Next, the solar cell matrix is placed onto the silicone. Another glass panel is coated with the encapsulant and is then turned upside down and placed onto the first panel containing the cell matrix. The whole sandwich is then introduced into a laminator, where a vacuum is drawn and the laminate is heated up, thus beginning the silicone curing process.

Implementation and manufacturing at BYD

A complete manufacturing process was designed on the basis of the module design, a preliminary silicone encapsulation process and an initial selection of other key components, such as the frame, junction box and PIB rubber. This process was first implemented, improved and fine-tuned on a pilot line. It was subsequently transferred to a manufacturing line, and high-volume production began; one of the fabricated modules is shown in Fig. 7.

Module performance, durability and safety

The electrical performance of the BYD double-glass modules was as expected for multicrystalline cells, with power bins ranging from 245W to 265W for 60-cell modules, and from 295W to 315W for 72-cell modules.

Accelerated ageing

The modules were subjected to numerous accelerated ageing tests. Table 1 shows the climate-chamber test data for damp-heat (DH), thermal-cycling (TC) and humidity–freeze (HF) tests. Only a small degradation can be observed, with at most around 1% after twice the duration of the standard tests prescribed by IEC-61215 (whereas this standard specifies a maximum permissible degradation of

Test type	Test duration	Relative power change [%]
Thermal cycling	TC200	–0.1
	TC400	–0.8
Damp heat	DH1000	–0.5
	DH2000	–0.9
Humidity freeze	HF10	–1.2
	HF20	–1.0
	HF30	–1.4

Table 1. Accelerated ageing test results.

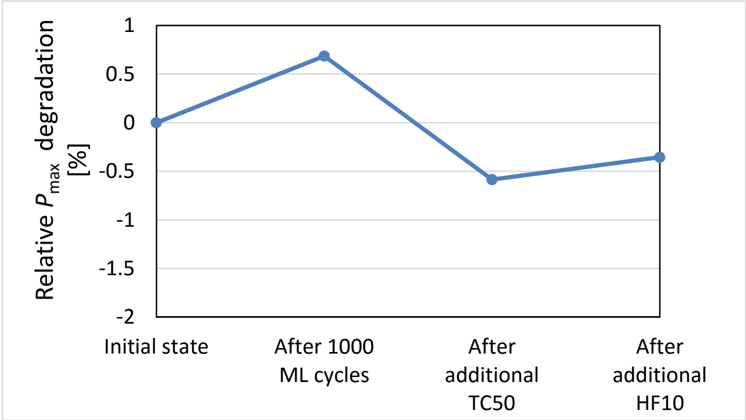


Figure 8. Module power degradation during combined mechanical load, thermal cycling and humidity–freeze test procedures.

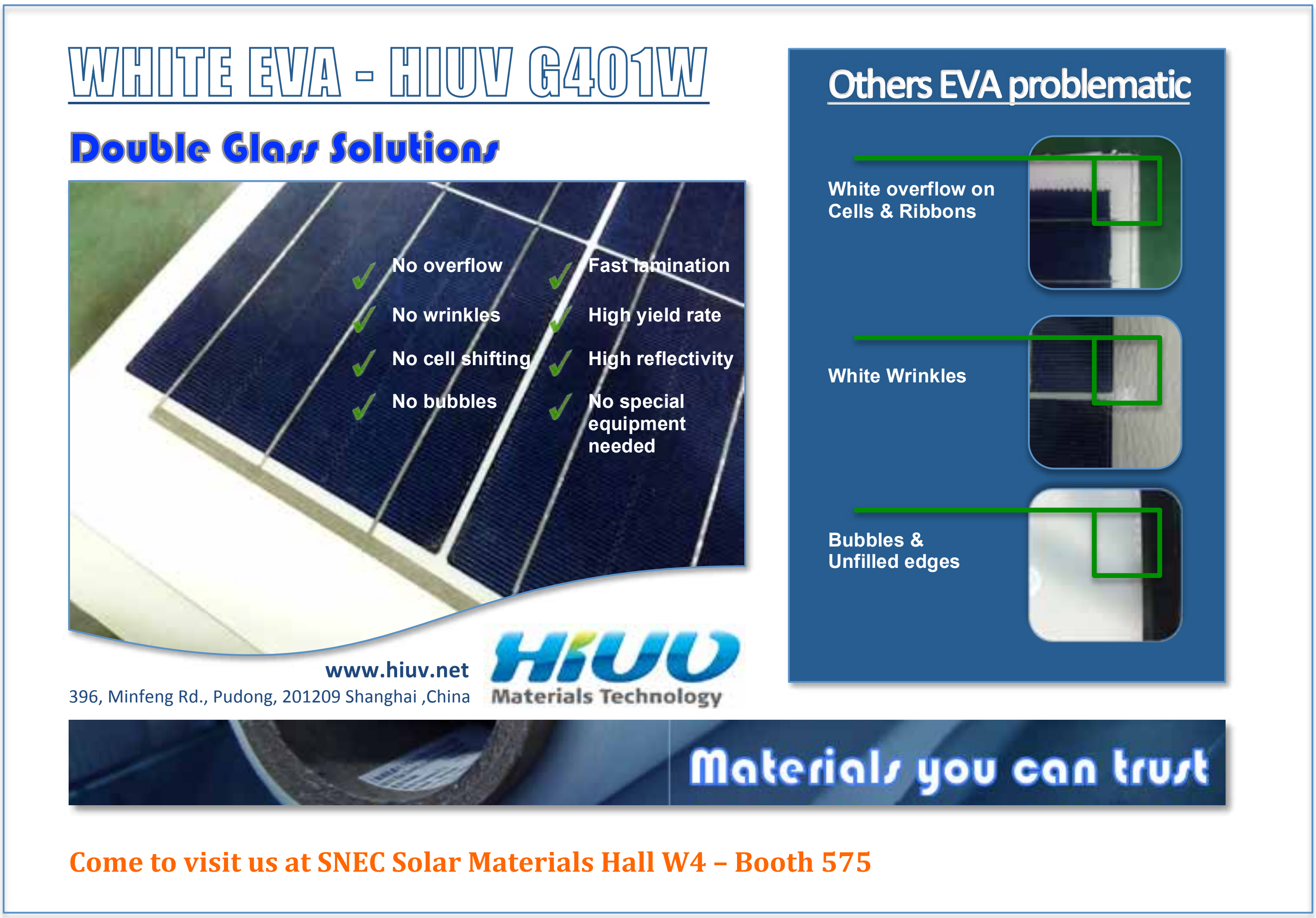
5% after 1×IEC). All the modules still comfortably passed wet leakage tests after accelerated ageing.

The results of a test combining dynamic mechanical testing (1,000 cycles, 1,440Pa), 50 thermal cycles and 10 humidity–freeze cycles are given in Fig. 8. As expected, the mechanical load has no negative impact on performance. The subsequent TC and HF tests reveal no significant damage to the strings, with a final degradation of less than 0.4% relative to the initial module power.

> “The double-glass module is extremely PID resistant.”

Potential-induced degradation

Another ageing phenomenon that must be tested is potential-induced degradation (PID). Over the last few years, PID has become a very important topic as PV systems become very large, resulting in long module strings and high operating voltage. The standard PID test involves keeping modules with metallic foil on the front surface in 85% relative humidity and 85°C conditions (85/85) for 96 hours under a potential of –1,000V, with a permissible power loss of 5%. After



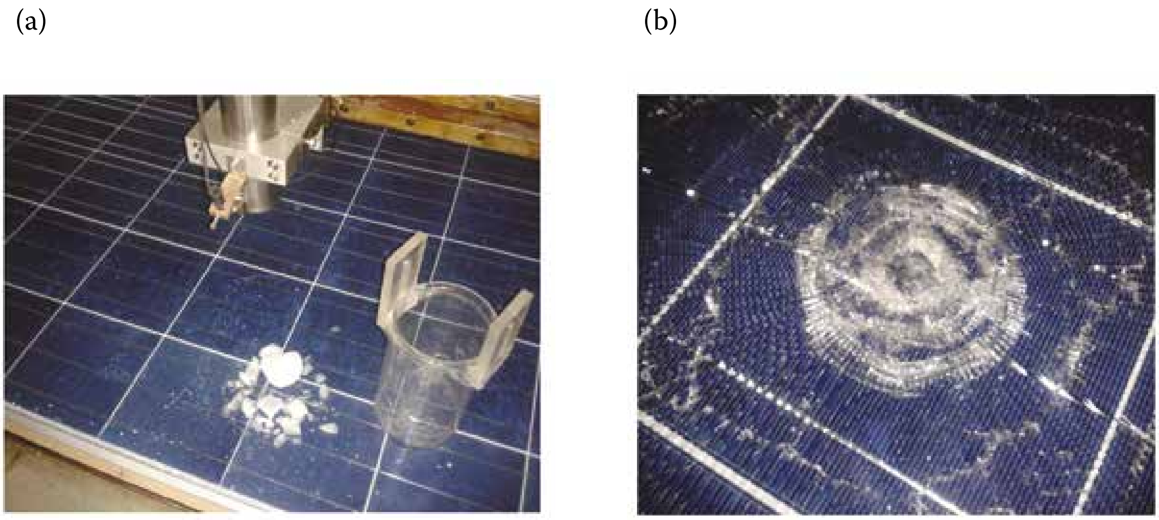


Figure 9. Results of the hail test (5cm, 126km/h) on (a) a BYD double-glass module, and (b) a conventional module with glass, EVA and backsheet.

192 hours of PID testing, however, the power loss of the tested module was only 0.6%. The voltage was then increased to 1,500V, and after an additional 96 hours, the power loss was still only 0.7%.

Another test involved applying 1,000V in 85/85 damp-heat conditions, but this time for 600h (both positive and negative bias). The power degradation was only 0.6% for +1,000V and 1.4% for –1,000V, which is an outstanding result for such a stringent test. It can therefore be concluded that the double-glass module is extremely PID resistant.

Hail resistance

The impact of hail was also investigated. This test consisted of projecting hailstones with a 5cm diameter at a velocity of 126km/h onto the module and observing the damage. As can be seen in Fig. 9, the double-glass module is intact, whereas the same test conducted on a conventional glass with EVA and backsheet results in substantial glass damage and module power reduction. The laminate rigidity, thanks to the double-glass structure, combined with the dampening effect to some degree of the silicone, appears to be very effective in preventing impact damage.

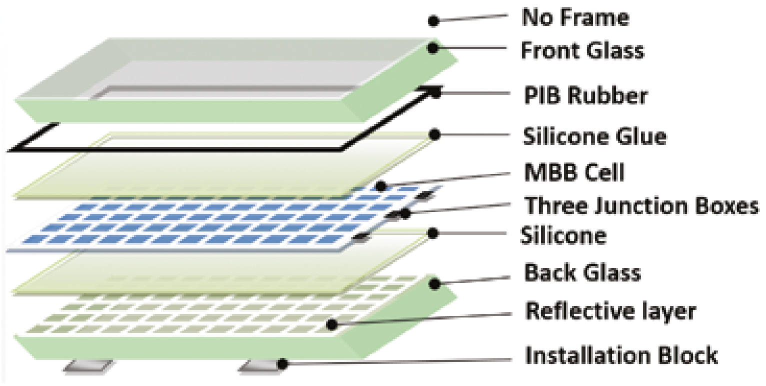


Figure 10. Schematic of 'PV Module 2.0'.

Module certification

A set of modules was submitted for certification to TÜV Rheinland: all the tests, carried out in accordance with IEC 61215, IEC 61730-1 and IEC 61730-2, were passed. Moreover, TÜV Rheinland did the electrical testing required for the new PV plant voltage standard of 1,500V. On the basis of the positive results obtained, for the first time for modules manufactured in China a certificate was issued confirming that these modules could safely be used in PV plants at operating voltages of up to 1,500V (compared with the current standard of 1,000V). The possibility of building systems that operate at higher voltages (i.e. more modules per string) allows significant PV system cost reduction, because fewer inverters are needed and the total cable length is decreased.

As a result of the outstanding reliability and durability data collected, the BYD double-glass module has been nicknamed the *430 module*. The first digit, '4', indicates that the products are estimated to work for 40 years. The middle digit, '3', means that the average annual power attenuation is as low as 0.3%. The last digit, '0', indicates that the module is PID free and exhibits no snail tracks.

Next generation of glass–glass silicone modules

In order to further increase performance and reduce cost, several innovations have recently been introduced, which have resulted in a new generation of glass–glass modules (Fig. 10). To reflect the momentous change that this type of module represents with respect to conventional modules, this technology has been named *PV Module 2.0*. The module is now totally frameless, and the interconnection ribbons have been replaced by 24 wires with a round cross section. The cells are 'multi-busbar' cells [9], featuring lots of very small solder pads instead of the three wide busbars conventionally used, onto which the wires are soldered.

This new structure allows a 25% reduction in silver consumption, as the total busbar area is less than that for conventional cells, and also because a lower finger cross section is permissible when the fingers are shorter. Moreover, because of the round shape of the interconnection wires, most of the impinging light is reflected onto the cell rather than back towards the sky, and therefore the short-circuit current and efficiency are increased. With this structure, a power of 275W has been obtained for a multicrystalline 60-cell module.

> "The combination of a glass–glass structure and silicone encapsulation leads to exceptional robustness, reliability and durability."

Conclusion

A novel double-glass module technology has been developed that makes use of silicone encapsulation. The combination of a glass–glass structure and silicone encapsulation leads to exceptional robustness, reliability and durability. These modules are particularly well suited to applications in harsh conditions and/or where very long module lifetime is required. Recent changes to the design, including the use of a multi-busbar design, have led to further improvements in cost and performance.

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About the Authors

Shencun Wang received his master's in 2010 from the Central South University of China. He joined BYD in 2010, where he leads a team involved in double-glass module application and process development. He has recently been appointed the production manager for double-glass modules.

Xiang Sun received his bachelor's in 2000 from the University of Science and Technology of China. He joined BYD in 2000, where he has held the positions of quality manager, production manager and project manager, and is currently the manager of the PV technology R&D centre.

Yujian Wu joined Dow Corning in 2012 as the Asia Pacific Application Development Leader for PV. Before joining Dow Corning, Yujian gained 12 years' experience in c-Si and thin-film solar, semiconductor IC fabrication and LED applications.

Yanxia Huang holds a Ph.D. in polymer Science from Tongji University, China, and worked for BASF and Henkel, focusing on acrylate adhesives, before joining Dow Corning in 2013. She is a senior product development chemist at Dow Corning China, working on materials for the construction and solar industries.

Nick Shephard joined Dow Corning in 1985, and has collaborated on products and processes for PV applications since 2004. He specializes in the field of surface science and adhesion durability, to which he has contributed patents, new products, new measurement techniques and global lectures.

Guy Beaucarne holds a Ph.D. from the University of Leuven, Belgium. After working as a PV researcher in Australia, he returned to imec, where he headed the Solar Cell Technology group for six years. In 2009 he joined Dow Corning, where he has been developing new materials and applications for PV, lighting and electronics.

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