Large area thin film solar module lamination

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ABSTRACT
The thin-film solar industry is entering a new phase of explosive growth. Large scale automated factories will use 5.7m^2 superstrates to achieve lower photovoltaic (PV) module production costs. This paper summarizes recent advances in encapsulating these large modules and providing high-quality environmental protection using polyvinyl butyral (PVB)-based packaging.

Introduction

The commercialization of a new generation of large low-cost thin-film silicon photovoltaic (PV) modules utilizes large-area deposition technologies first developed for the manufacture of flat panel displays (FPD) such as liquid crystal televisions. Equipment has been introduced in which 2.2 x 2.6 meter glass superstrates are processed, allowing significant fabrication cost reductions. There is also a need to develop long-lived packaging materials usable at this superstrate size.

Material requirements

Polyvinyl butyral (PVB) was first utilized for solar photovoltaic modules in the 1970s [1]. Early modules incorporated PVB formulations that absorbed water at exposed edges, resulting in a cloudiness characterized by a loss in visible light transmission. As a result, solar module manufacturers shifted for the most part from PVB to ethylene vinyl acetate (EVA) for use in many solar cell applications [2]. In 1997 a 'third generation' PVB interlayer that mitigated the cloudiness issue was introduced to the glazing market. With the introduction of the third generation formulation, PVB is now ready for full-scale use in the solar industry, particularly for thin-film (TF) glass/glass applications. Factors that make PVB the best pottant material for high-quality, long-lived TF silicon modules include:

Availability – Relative to EVA, PVB is more readily available worldwide due to its use in the automotive and architectural industries.

Fire rating – PVB has a better fire rating than EVA.

Safety glass rating – PVB is broadly specified for building code performance.

Re-workable – PVB is a thermoplastic and is more easily re-worked than is cross-linked EVA.

Performance/cost – PVB is superior to EVA in overall performance relative to net cost.

PVB formulations

Unlike EVA, there are dozens of different formulations of PVB for use in the automotive and architectural industries. Available PVB products include formulations for improved impact strength; adhesion to glass, adhesion to metals, transmission tuning, creep reduction, and sound dampening as well as many other applications. The resulting depth and breadth of the PVB product line make it an ideal candidate for the development of TF optimized solar inter-layers. Key TF performance criteria such as long term durability, environmental protection, electrical isolation and cost can all be optimized.

Water sensitivity

Polyvinyl butyral is a hydrophilic material that will gain or lose moisture depending on the environment to which it is exposed. The moisture content of PVB, typically manufactured at 0.4% by weight, rapidly changes with exposure to the atmosphere. Figure 1 shows the equilibrium water content of a typical PVB formulation as a function of environmental humidity level (moisture uptake is dependent on many variables).

Once laminated, glass/glass solar structures incorporating PVB inter-layers are affected by humidity at the modules' exposed edges. In the field, PVB at the edges of the cells quickly reaches the moisture equilibrium dictated by the environment (see Figure 1). Natural fluctuations in humidity, both on a daily and seasonal basis, result in a cycling of PVB edge moisture with time. The slow diffusion of moisture through the PVB results in the interlayer inward of the two-millimeter perimeter of the TF module remaining unchanged by environmental conditions.

Increasing the moisture content of a PVB interlayer reduces its adhesion to glass. This phenomenon is reversible, however, with a return to original adhesion values as the PVB dries out with normal environmental fluctuations. The inter-layer formulation can be modified to further reduce adhesion sensitivity to moisture that may be absorbed at laminate edges.

Moisture sensitivity can also have an impact on the module's high voltage leakage current characteristics. Figure 2 shows the bulk resistivity effect for two particular PVB formulations for different moisture absorption levels. An awareness

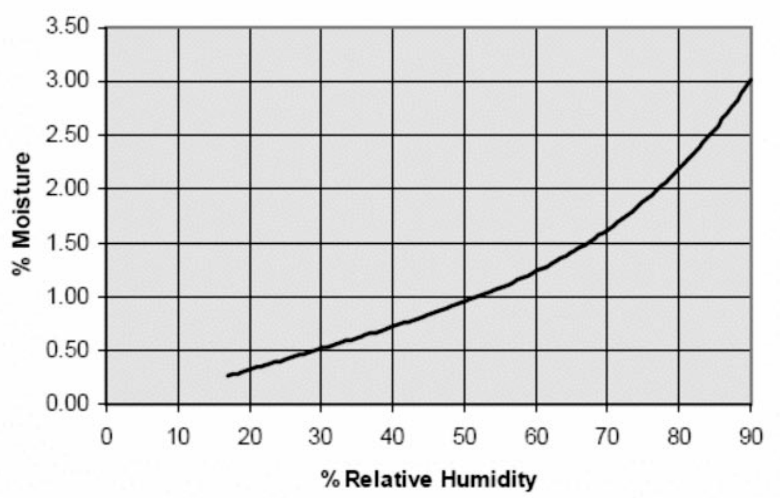

Figure 1. PVB equilibrium moisture content as a function of relative humidity.

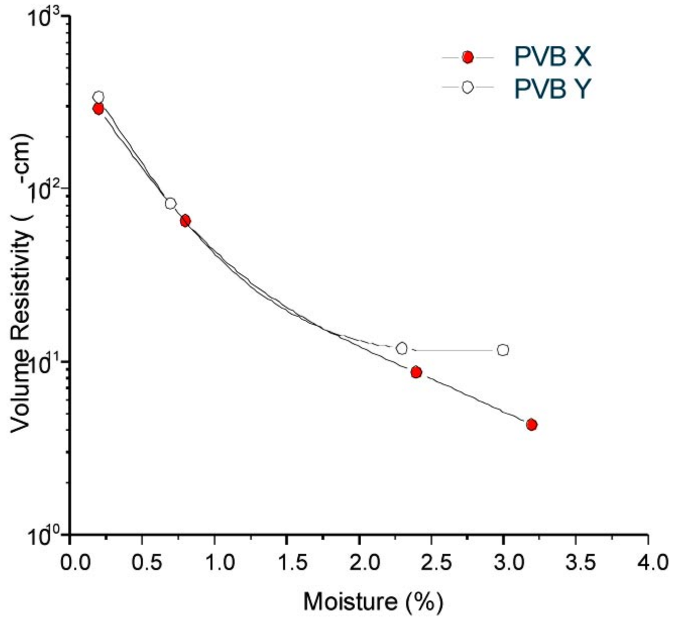

Figure 2. PVB resistivity as a function of moisture content.

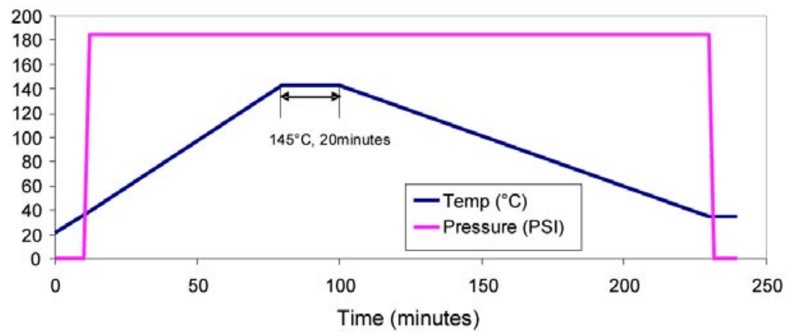

Figure 3. Autoclave cycle.

of this effect must be part of the module design in order to control module leakage currents.

De-airing process (assembly bonding)

PVB lamination is a three-step process of lay-up, de-airing, and autoclaving. The lay-up step consists of assembling the module by stacking the solar plate (circuit), PVB layer, and back glass and trimming excess PVB from the edges of the lay-up stack. De-airing – the removal of interfacial air trapped between the various components – follows the lay-up step. De-airing can be commercially achieved through any of three processes:

1. Vacuum lamination: in the vacuum de-airing process, the assembled lay-up stack is placed in either a vacuum laminator (used in the solar industry) or a vacuum bag (used in the automotive industry). The assembly is heated to about 55°C while under vacuum to remove most internal air, and is then raised to about 95°C to seal the module edges.
2. Vacuum ring: in the vacuum ring de-airing process, custom made flexible channels seal the periphery of the assembly. A vacuum is applied to remove internal air while the laminate is heated to between 70°C and 95°C.
3. Nip rollers: in the nip or calendar roll de-airing process, the plate/PVB/glass stack is heated and then passed between mechanical rollers that physically squeeze the assembly together and push air from between the PVB and the glass. This is a cost-effective approach that is widely used in both architectural and automotive lamination. The nip roll de-air process can utilize any of several sequences of heating and pressing.These sequences are:
   a) 1 oven followed by 1 nip roll system (a.k.a. 1 oven, 1 nip)
   b) 1 oven preceded and followed by a nip roll system (a.k.a. 1 oven, 2 nips)
   c) A sequence of oven, nip, oven, nip (a.k.a. 2 ovens, 2 nip)

The most common lamination process is (c); our recent work has focused on this approach.

Autoclave cycle

The autoclave process completes the PVB lamination process by subjecting the parts to high pressure and temperature. These conditions allow the PVB to flow around obstructions, filling any voids left from the de-air step and dissolving any residual air into the PVB interlayer. Figure 3 shows the process cycle that was used for fabricating 5.7m^2 laminates. The duration for which the system must be held at maximum temperature and pressure (hold time) is a function of the quantity of material loaded in the autoclave in a single batch as well as the autoclave size and shape. Larger batches of PV modules generally require longer hold times than batches with fewer modules in order to ensure that all modules reach PVB processing temperatures.

Thin film solar module design

Although the thin-film deposition steps are all done at the 5.7m^2 size, finished modules were produced in four sizes. The electrical characteristics of eight module designs in these four sizes are shown in Table 1.

					Single Junction			Tandem Junction		
Design	x(m)	y(m)	# Cells in Series	Cell Area (m2)	V_{oc}(V)	I_{sc}(amps)	P_{max}(W)	V_{oc}(V)	I_{sc}(A)	P_{max}(W)
1	2.2	2.6	216	0.246	195.5	2.9	343.3	289.4	2.6	457.5
2	2.2	1.3	216	0.122	195.5	1.5	170.3	289.4	1.3	226.9
3	1.1	1.3	106	0.122	95.9	1.5	83.6	142.0	1.3	111.4
4	1.1	2.6	106	0.246	95.9	2.9	168.5	142.0	2.6	224.5
5	2.6	2.2	256	0.208	231.7	2.5	344.1	343.0	2.2	458.5
6	1.3	2.2	126	0.208	114.0	2.5	169.3	168.8	2.2	225.7
7	1.3	1.1	126	0.1025	114.0	1.2	83.5	168.8	1.1	111.2
8	2.6	1.1	256	0.1025	231.7	1.2	169.6	343.0	1.1	225.9

Table 1. Anticipated initial module performance as a function of module design.

Following the analyses summarized in Table 1, bus and cross ribbons are designed to meet <1% active area loss and <1% resistive losses. This requirement resulted in a 4mm wide x 0.12mm thick bus ribbon, an 8mm wide x 0.12mm thick cross ribbon, and a 19mm wide x 0.02mm thick polymeric insulation tape. The resulting stack at the attachment points could be up to 0.26mm thick. This thickness of the bus and cross ribbons complicates the de-airing process by creating a discontinuity in the surface that tends to act like a dam, blocking interfacial air flow out of the assembly, and reducing PVB contact to the cell during the nip-roll de-air process.

Results

30cm x 30cm TF silicon modules were used to facilitate PVB lamination process development. All modules were manufactured with the same key dimensional specifications as the 5.7m^2 modules, i.e. 12mm edge deletion, 8mm bus width, and bus, cross bus ribbon and insulation tapes as described above.

Nip performance effects

As previously stated, the lamination process consisted of a two-oven, two-nip de-air step followed by an autoclave step. In the de-air step, the laminate passes through the first oven, the first nip, the second oven and finally the second nip. The role of the primary oven and nip is to heat the PVB to an optimal temperature for tacking to glass and to bond the assembly while expelling a majority of the entrained air. The secondary oven and nip further heat the assembly and apply additional pressure to form a seal around the edges of the laminate.

The subsequent autoclave step promotes PVB reflow around obstructions (i.e. bus and insulation tapes), and dissolves any residual entrained air. The abrupt steps created by the bus wires on the back of TF modules make lamination more difficult. The surface topography and flow properties of the sheet must be optimized for improved processability of the interlayer. As shown below, PVB flow, thickness and temperature are critical to lamination performance.

Performance vs. PVB types

Different PVB formulations strongly affect lamination performance. PVB flow is among the most critical properties, affecting the amount of residual air after the second nip roll. A typical post-nip bubble is shown in Figure 4. The amount of residual air can be inferred by the number of bubbles visible following the autoclave step. PVB interlayers with improved flow at elevated temperatures tend to conform better to surface variations, and make it easier for air to be pushed out by nip roller press. Table 2 ranks the de-airing quality resulting from the use of different grades of PVB. The table shows clear correlation between PVB flow and lamination performance.

PVB type	Adhesion	Roughness	Flow	Ranking
A	high	medium	medium	6
B	medium	medium	medium	3
C	medium	medium	medium	5
D	medium	high	medium	7
E	low	high	high	2
F	medium	medium	high	1
G	high	medium	medium	3

Table 2. Impact of PVB properties on lamination performance.

Figure 4. Typical post-nip bubble patterns for 0.2mm wide bus ribbon.

Splits	First Nip Temp (°C)	Second Nip Temp (°C)	Ranking
1	25-35	50-65	6
2	35-45	65-75	5
3	45-55	75-85	3
4	55-65	85-95	1
5	65-70	95-100	1
6	>80	>105	4

Table 3. Impact of temperature on lamination performance on a 1.14mm thick type G PVB film.

Performance vs. temperature

Because PVB is a thermoplastic, the polymer softens with increased temperature. For laminates with rougher surfaces, extra flow or higher pre-nip oven temperatures are needed to ensure more complete de-airing. While many flat glass laminators use room temperature for first nip rolling operation and 140°F for second nip, it was found that PV modules needed higher temperatures, especially higher module temperatures, when entering the first nip roller. Table 3 shows performance of the same PVB type for different oven temperature settings. One can see that performance improves with increasing temperature, until temperatures exceed the point at which premature edge sealing occurs.

Performance vs. PVB and bus wire thickness

Experiments demonstrated that PVB thickness plays a very important role in lamination performance. Increased PVB thickness results in a more compressible interlayer that is better able to conform to the thickness variations of the solar cell components. Thicker PVB also increases the capacity of the interlayer for dissolved air. By the same logic, modules with thinner bus wires provide smaller obstructions that are easier to laminate, at a given interlayer thickness. Improvements to lamination performance from thicker PVB, thinner bus wire and high surface roughness PVB are shown in Table 4.

Baseline PVB choice

Per the overall results, and balancing both cost and performance, 1.14mm thick type G film appears to be optimal for thin-film lamination. In order to study other quality requirements of the PVB choice, we produced standard laminations, completed the standard autoclave cycle, and then conducted adhesion testing.

Shear testing

Shear testing is performed by cutting a circular 2.5cm diameter sample from the laminate and shearing it until the laminate fails at an interface. Shear testing of a type F PV sample yielded very good results: failure at 13.2MPa with a standard deviation (σ) of 1.5MPa. All failures occurred at the metal/PVB interface. As a guide, typical shear strengths for glass/glass lamination range from 13-19MPa.

Split	PVB type	Thickness (mm)	Bus wire (mm)	Ranking
1	G	0.76	0.2	6
2	G	1.14	0.2	3
3	G	1.52	0.2	1
4	G	0.76	0.1	3
5	E	1.76	0.2	3
6	E	2.76	0.1	1

Table 4. Impact of PVB and Bus Wire Thickness on lamination performance. Performance is based on count of air bubbles after lamination.

Bake testing

Bake testing is a common test carried out in the lamination industry in which laminates are baked for 16 hours at 100°C and then subjected to 10°C increases in temperature until bubbles begin to form within the laminate. Bake testing is typically carried out to determine if excessive amounts of air have been trapped in the laminate during the lamination process. For example, a laminate failure temperature – i.e. the temperature at which bubbles begin to form – below 130°C is a typical predictor of poor laminate durability. Table 5 summarizes the results of bake testing on PV samples.

Leakage current testing

Modules were exposed to 1000 hours of 85°C/85% relative humidity per standard IEC testing. The PVB interlayer showed no discoloration, no bubble generation or delaminations. Wet hi-pot testing was done to make sure the module leakage current was in specification. Figure 5 shows that the resulting leakage current translated to the 5.7m² size module would only be 25% of the maximum allowed.

Large area laminations

Extensive lamination studies have been conducted using 1.4m² (1.1m x 1.3m) and 5.7m² (2.2 x 2.6m) sizes, and the same baseline processes have proven successful at these sizes. Figure 6 shows a successful

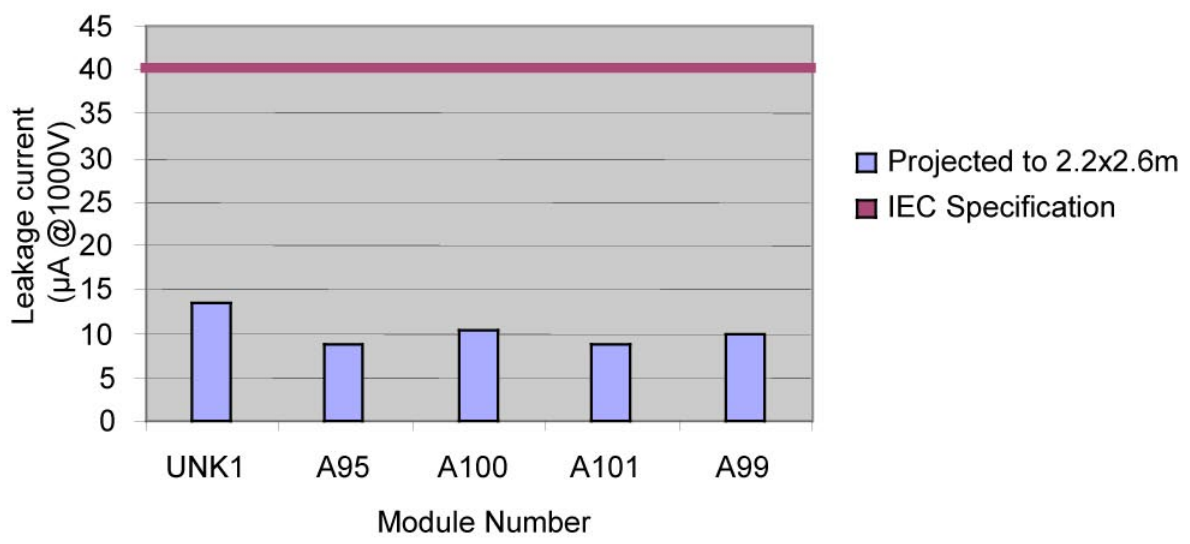

Figure 5. Module leakage current after 1000 hours 85%RH/85°C using grade F PVB

Split	PVB Grade	Thickness (mm)	Bus (mm)	100°C	110°C	120°C	130°C	140°C	150°C	160°C	170°C	180°C
1	E	0.76	0.2	0	0	0	0	0	0	2	2	15
2	E	0.76	0.1	0	0	0	0	0	0	0	0	4
3	G	1.14	0.2	0	0	0	0	0	0	0	2	2
4	G	1.14	0.2	0	0	0	0	0	0	0	1	1
5	G	0.76	0.2	0	0	0	8	8	8	8	8	8
6	G	0.76	0.1	0	0	0	0	12	12	12	12	12

Table 5. Bake tests results.

Figure 6. Post autoclave (no bubbles).

nip process for 5.7m^2 glass and a bubble-free autoclave finished laminate.

Conclusion

We have successfully developed a robust PVB process using nip roll plus autoclave lamination technology, and have identified a PVB grade which meets the TF solar module requirements. The process and material produce laminates with excellent adhesion, environmental integrity and meets all cost and quality targets.

Acknowledgments

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References

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