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Vacuum-free, cost-effective, developing-country-material-available solar cell encapsulation

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Abstract

We describe a novel cast encapsulation method based on room-temperature vulcanizing (RTV) silicone. This method does not require vacuum, nor lamination, and all the material needed, except for the encapsulant itself is available in developing countries. It is successfully used in Nicaragua. In addition, we report in detail on a recently developed solution to limit trapping of bubbles in the encapsulant during curing. We deposit, prior to encapsulation, a thin film of RTV silicone on the cells. The resulting solar panels made using this technique show a lot less trapped bubbles.

Keywords: Vacuum-free encapsulation; Cast encapsulation; Silicone encapsulation

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1. Introduction and context

The encapsulation of solar cells into a solar module ensures good mechanical properties and protection against moisture that would rapidly lead to contact corrosion, and electrical characteristic degradation. In state-of-the-art solar modules industry, the module assembly (including materials) accounts for 30% of the cost of the solar panel [1]. It also represents more than 10% of the energy needed to build a solar panel, among which more than half is dedicated to the lamination step [1,2].

Standard encapsulation of industrial silicon solar cells is obtained by stacking a front cover, a layer of encapsulant material, the cells tabbed into strings, another layer of encapsulant material, and a backsheet. The front cover usually consists of hardened glass, the encapsulant is a material especially designed for solar cell encapsulation (ethylene vinyl acetate (EVA)) [3], and the backsheet usually consists of a fluoropolymer Tedlar™ sheet. The stack is then put into a laminator where a vacuum pump removes the air between the sheets, melts the encapsulating material by heating the panel to 150 °C, and applies mechanical pressure to remove air bubbles as well as to maintain the string position. The laminate is then sealed (with elastomer), framed (with aluminum), tested and packed for shipping. This flow chart is reliable and warranties a panel lifetime over 25 years [2]. But it is energy consuming and necessitates the use of a laminator. In places where energy is scarce and a laminator is a far too costly investment, alternative ways of encapsulation have to be worked out.

In Madriz, a northern and rural region of Nicaragua, the Grupo Fénix, a non-governmental organization, started in 1999 a module-assembly workshop with two main goals: supplying electricity to off-grid rural population (60% of the population of Nicaragua is currently not connected to the electricity grid) and rehabilitating mine-land victims (people working at the workshop are all mine victims from the civil war in the 1980s) [4].

This article first describes the process that is used in the Grupo Fénix workshop to encapsulate cells within the local constraints (expensive access to electricity, no laminator, only basic material commercially available). Then the assets and limitations of the process are discussed. Finally, experiments are carried out to improve the reliability of the panels. A new process flow is then proposed.

2. Encapsulation process description

Fig. 1 illustrates the encapsulation process, which is also described in Ref. [5]. As a starting material, the workshop uses broken or lower class mono-crystalline Si cells from northern countries' solar cells industries. The cells are cleaved to remove the broken part, all at the same dimensions to ensure the current matching (see Fig. 1(a)). Only a scribing tool (and a lot of care) is necessary at this step.

Open-circuit voltage and short-circuit current are measured in the sun (natural sun) to estimate roughly the cell quality. The cells are then hand-soldered into strings (see Fig. 1(b)), which are again tested in the sun. The tab connecting one cell to another is left on purpose longer than required to cover the distance between two cells in the module. The excess length forms a loop that will relieve the stress due to differential thermal expansion of the glass and the cells, during everyday thermal cycles. If at this stage the string

Fig. 1. Module encapsulation process description. (a) Cutting the cells, (b) soldering, tabbing and stringing the cells, (c) casting the strings into a silicone bath and (d) testing the panel in natural sunlight.

characteristics measured at the sun are not satisfactory, each cell is tested independently and the weak cells are replaced.

The cells are encapsulated with no use of a laminator (this type of encapsulation is often referred to as "cast encapsulation"): a piece of standard window glass is first cut at the desired dimension, and framed with aluminum. The use of standard window glass instead of tempered glass makes the rigidity of the structure more critical. Nonetheless, window glass is more easily available in Nicaragua, cheaper and easier to replace in case of module breakage (tempered glass shatters into small pieces). To improve the mechanical stability, a square-section aluminum frame has been adopted. The glass is cleaned with acetone.

Two-component room-temperature vulcanizing (RTV) liquid silicone (Dow Sylguard 184) is poured on the framed glass. The mix of the silicone base and of the curing agent is carefully adjusted. Adding too much curing agent allows a faster curing, but reduces adhesion and results in delamination. The silicone bath is rested for a few minutes to allow trapped air bubbles to come out of the liquid.

The cell strings are then positioned face down on the silicone bath (see Fig. 1(c)). Some pressure is gently applied to allow air bubbles to escape from underneath the cells. A second layer of liquid silicone is poured onto the back of the cells to ensure complete moisture sealing.

Fig. 2. Advertisement stand of the Grupo Fénix workshop during a local event.

The module is then kept in a closed room for drying. After 10 h drying, the strings are soldered together, and a plastic backsheet is applied on the silicone. A second window glass is then added to the back of the module, including an opening to allow electrical connections to exit the module. This glass is maintained in place by riveting aluminum "L"-shaped bars to the aluminum frame. Some plastic is melted into visible moisture protection weaknesses (such as electrical wire openings) to further increase the watertightness of the module. Although the second glass does not really participate in the watertight barrier, it provides protection for the silicone and additional mechanical strength to the module.

The finished module is cleaned and tested in the sun (see Fig. 1(d)).

The modules produced in the workshop in Madriz are used to provide electricity to surrounding off-grid villages. Fig. 2 shows a picture of an advertisement stand of the Grupo Fénix workshop during a local event.

3. Assets of the encapsulation process

The encapsulation process, as it is described above, carries some major assets over conventional encapsulation.

First of all, almost all the module materials (soldering material, standard glass, aluminum frame, acetone, and plastic backsheets) are commercially available in Nicaragua, which is not the case for more specific materials used in the photovoltaic industry, for instance Tedlar^{TM} sheets, EVA, etc. This is in fact a necessary condition for producing solar panels in Nicaragua at reasonable cost, since the supply of imported products can be irregular and expensive. The Dow Sylguard silicone is not yet commercially available in Nicaragua, and is the only exception to this rule.

In addition, the only energy consumption of the process comes from the soldering irons. The module assembly cost (investment and energy costs), as well as the energy payback time, are thus reduced.

Furthermore, the panel can be pulled apart for repair and a small amount of fresh liquid silicone can fill in the hole(s) after repair. State-of-the-art industrial vacuum-lamination-assembled modules (using EVA and tempered glass) do not yet allow repairing and are just discarded and replaced when broken [6].

Finally, the process is very robust and reproducible, and leads to very professional-looking panels. Unlike other encapsulation materials (see for instance Refs. [3,7]), Dow liquid silicone has proven to be a very UV-stable encapsulant. In fact, although the workshop has no access to accelerated ageing test facilities, no encapsulant browning nor delamination has been observed so far on our modules, even for panels assembled with a very similar process flow in the 1970s.

4. Limitations of the encapsulation process

Two main limitations nonetheless raise questions about employing this process at a wider scale. First, cell breakage occurs from time to time during string manipulation and repositioning in the bath. Secondly, some bubbles remain trapped in the dry silicone. The latter is a recurrent problem of module assembly processes [8]; bubbles increase the amount of reflected light and may lead to enhanced corrosion of the contacts. In addition, during every day thermal cycles, expansion and contraction of the bubbles might lead to delamination. We recently developed a new process flow addressing these two weaknesses.

5. Experimental set-up

In the standard process, bubbles are formed during drying of the panels (no bubbles are visible just after casting). Besides, they are mainly localized at the cell–silicone interface. They are thus assumed to be mainly consisting of air desorbing from the surface irregularities due to soldering, and from the textured solar cell surface itself.

The modified process includes an additional step: before casting, we pour a thin film of liquid silicone on the front side of the cell strings. We dry this film and then we position the strings, capped with this (now dry) silicone film, face down on a fresh liquid silicone bath just like we do in the current process. The end of the process is then carried out as before.

This additional step is meant to deliver two main improvements to the current process: the bubbles can easily escape during drying of the silicone capping film, and the capped string is a lot easier to manipulate without breakage.

Table 1
Experimental conditions to limit the number of bubbles trapped into the silicone

	Silicon capping film	Pressure	Remark
Set A	No	No	Reference
Set B	Yes	No	Capping film dried in sun
Set C	Yes	No	Capping film dried in house
Set D	Yes	Yes	Capping film dried in house
Set E	No	Yes	Broken while under pressure

Five experimental conditions were applied each time to two tabbed cells of dimension 3.5 cm × 7 cm. Table 1 summarizes these conditions.

Set A, as reference, does not have any silicone capping film, and no pressure is applied during drying of the silicone bath. On sets B and C we poured and dried a silicone film before positioning the string in the silicone bath. No pressure was applied during the drying of the silicone bath. These two sets differ by the fact that for set B the silicone cap was dried in the sun (>40 °C, direct sunlight) for 1 h, and for set C the cap was dried indoors (~25 °C, ambient light) for 10 h. A fast drying makes the whole process faster, but may give less chance to the air bubbles to escape during drying of the cap. Set D has a silicone cap, and we applied some pressure on the cells during curing of the silicone bath. Set E has no silicone cap, but we applied some pressure during drying. The pressure was applied manually during the first 20 min of drying. The cells of set E did not withstand the manual pressure and rapidly broke when the pressure was applied. The mini-panels were let for drying for 10 h indoors (~25 °C, ambient light), following the initial process flow.

6. Experimental results

Meanwhile set E was discarded because the cells did not withstand the manually applied pressure conditions, the cells of set D did withstand the same pressure conditions. The dry silicone capping film is thus a good mechanical strengthener to avoid breakage during string manipulation and application of pressure conditions.

After complete drying of the silicone bath, we visually compare the four sets of conditions A, B, C, and D. Fig. 3 shows the pictures of the four sets of cells. The difference between set A (reference) and sets B, C, and D is striking. A lot less bubbles are visible on the cells where a silicon capping film was deposited before casting the string in the silicone

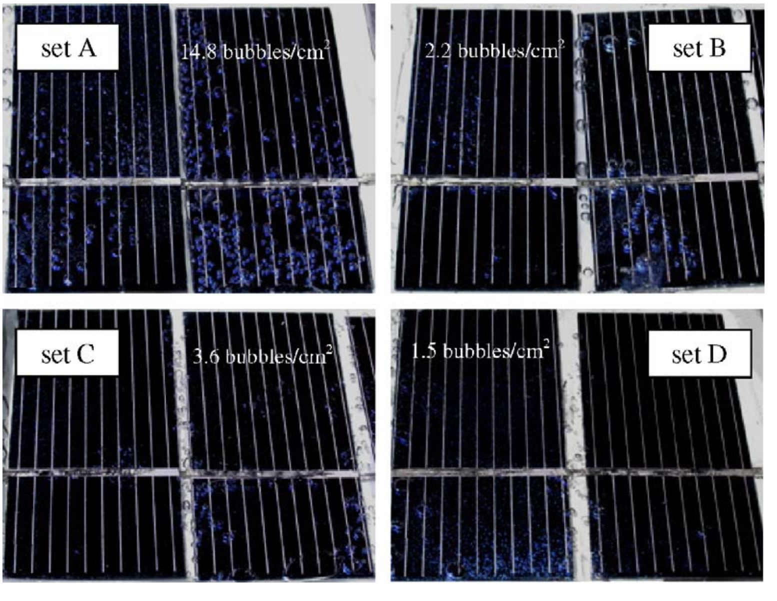

Fig. 3. Resulting aspect of encapsulated solar cells with the different experimental conditions. The average density of bubbles countable on the encapsulated solar cells is included for each experimental condition.

bath. To put it even more clearly, we counted on each cell the number of visible bubbles, and reported the average density of countable bubbles for each set of conditions in Fig. 3. Set A (no silicone capping) shows almost four times as much bubbles than the cells on which a silicone capping was spread. As explained above, it is believed that the air trapped in the roughness of the cell surface already escaped during the curing of the silicone capping film. In addition, during the positioning of the capped cells, the surface in contact with liquid silicone is smoother and thus gives less chance to air bubbles to be trapped. Therefore, depositing a silicone capping film on top of the cells before casting them into the silicone bath clearly reduces the trapping of bubbles in the final module.

Besides, sets B and C show almost no difference. Even while fast drying the silicone cap in the sun, no bubbles were visible between the cell string and the thin silicone cap before positioning them onto the fresh silicone bath. Set D experienced a little fewer bubbles than sets B and C, but the bubbles have not been completely pushed out. A closer look reveals that the bubbles remaining above sets B, C, and D are larger in size than the multiple ones above set A. In addition, the bubbles remaining in sets B, C, D are lying between the two silicone layers, meanwhile for the standard process, the bubbles appear at the cell–silicone interface. Two conclusions stem from this observation:

First, we attribute our failure to remove all the bubbles to the cumbersome way we manually applied the pressure. Applying a higher and more homogeneous pressure (for instance using card-box and handscrews) would probably help pushing out the last air bubbles.

Secondly, because the bubbles are not in contact with the cells, even if thermal cycles eventually lead to gas expansion, the solar cells of sets B, C, D are likely to remain protected from moisture by the unaltered silicone capping film. The weak interface has been transferred from the critical cell–encapsulant interface, where delamination is usually observed [9], to a less harmful and more elastic silicone–silicone interface.

Because they do not necessitate soldering on the front surface of the cells, back-contacted cells would also be very helpful for cell encapsulation using the casting process described in this article. The front surface of the cell string would be flatter and thus less air trapping and less sensitive to breakage under pressure.

7. Conclusion

We have used full-casting encapsulation of Si solar cells in a silicone bath to build modules within the restrictive conditions of a third-world-country rural region workshop. Strings of cells are soldered and positioned in a silicone bath, which is let for drying. One recurrent problem is that some bubbles are trapped in the silicone during curing. To circumvent it, we propose an additional step in the process: we cover the cells with a thin film of silicone before casting them in the silicone bath. The resulting samples clearly show a reduction of the number of bubbles retained in the silicone. In addition, the additional step enables easy manipulation and repositioning of the cell strings, as well as pressure application on the cells during drying of the silicone bath to push the last air bubbles out. The new encapsulation process, including this additional step, remains vacuum-free, cost-effective, and developing-country-material-available.

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