PRODUCTION OF RECYCLABLE CRYSTALLINE SI PV MODULES

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ABSTRACT: In this paper we investigate new approaches to enhance recovery of valuable materials during the recycling of crystalline Si (cSi) PV modules. The recycling of out-of-specs, damaged or end-of-life cSi PV modules will gradually become more important for PV suppliers and recyclers. Also recycling can help to further reduce carbon and environmental footprint of cSi PV. We tested two approaches to enhance recyclability of frame, glass, and silicon. The research was based on ECN's conductive back-contact module technology. First, alternative edge sealants, easy to release from the module, were tested on their protection against air and moisture ingress into the module. Several alternatives were established which show comparable protection as the state-of-the-art silicone-based or double-sided adhesive tape edge sealants, but are much more easy to remove. Second, thermoplastic encapsulant was investigated as a method to improve recyclability of PV modules. The thermoplastic encapsulant used in this study results in PV modules with improved resistance to damp heat (DH) conditions, compared to EVA-based modules. The separation of the components (cells, glass, backsheet) in PV laminates with this thermoplastic encapsulant, using a wire saw device at temperatures around 200 degrees C, was demonstrated. This method may allow recovering of intact solar cells out of end-of-life, out-of-specs or damaged PV modules.
Keywords: PV modules, crystalline silicon, Recycling, Thermoplastics, Encapsulant, Edge sealant

1 INTRODUCTION

The current H-pattern crystalline Si (cSi) PV modules have a guaranteed technical lifetime of 20-25 years and their installation started in the mid 80's. The number of end-of-life modules and modules damaged due to extreme weather conditions has increased significantly [1]. Since 13 August 2012, the recast WEEE (Waste Electrical and Electronic Equipment) Directive 2012/19/EU provides a legislative framework for extended producer responsibility of PV modules at European scale. As from 14 February 2014, the collection, transport and treatment (recycling) of photovoltaic panels is regulated in the European Union (EU) countries [2,3].

The current state-of-the-art recycling process aims at recycling of more than 80% of the PV module by weight [3]. The process flow begins with removal of the aluminum frame and junction box. Because the size, profile and fastening of frames varies between manufacturers, the frame is often removed manually. The frameless PV laminate consists of the active silicon cell embedded in a layer of Ethylene Vinyl Acetate (EVA) polymer, which bonds the tough polymer back sheet and the glass front sheet. Under the hammer mill, the laminate is shredded to fragments of glass, back sheet, wiring and silicon solar cells (wafer with small amounts of metal) still embedded in EVA. The main resulting fractions are separated and classified as products such as clean glass used in the packaging industry, contaminated glass with EVA and solar cell fragments used as isolation glass. Also the tin plated copper tabs are recovered. The remaining fraction of "fluff", consisting of smaller particles, dust, fibers, and polymers, is not subjected to a further separation procedure but is stored in big bags or dumped as landfill.

The target of the research described in this paper is reducing the environmental footprint [4] and looking for ways to increase profit from recycling. The first approach to reduce environmental footprint can be reduction of materials use, especially of scarce (silver) or harmful (lead) materials, or materials with high energy footprint (silicon). The second approach is then to maximize (within economic constraints) the recovery of the most important materials. ECN back contact technology already reduces consumption of silver (it allows short metallization "fingers" on the cell), silicon (it allows very thin wafers) and lead (it doesn't employ solder). In this work we investigate ways to optimize recycling of these modules.

The preferred recycling method would be a cheap, cost effective process resulting in a maximum amount of separated high-value materials that could be re-used in production of new PV modules or in other industrial applications. This would reduce the amount of scarce and expensive materials and also reduce the carbon footprint of PV modules.

The previously investigated methods for recycling aiming for more materials recovery (in particular, of silicon) from the standard EVA-based PV modules include pyrolysis, fluidized bed reactor or dissolution in organic solvents or strong acids [5,6]. Especially for the methods in which elevated temperatures are required, high energy consumption is needed, and the risk is that low-quality separated PV module components result. The business case for these separation techniques are still weak, partly caused by relatively low volume of collected end-of-life PV modules, partly due to the high process cost and a low value of the separated components.

In the research reported here, we aim to improve the recyclability of PV modules by replacing EVA with a more recycling-friendly thermoplastic encapsulant, e.g., a Thermoplastic PolyOlefin (TPO). The application of thermoplastics in PV modules can ease a proper separation of the module components, with possibility of recovering entire cells. The separation method and first preliminary results will be described in this paper. Importantly, replacement of encapsulant should not impair the module performance and lifetime. The reliability of TPO incorporated in PV modules is therefore investigated in this paper by testing PV modules under damp heat (DH) and thermal cycle (TC) conditions according to IEC61215.

The traditional module edge sealants, e.g, silicone-based edge sealants from Dow Corning (PV804) or a double-sided adhesive tape (Duplomont® 918), result in a strong connection between the aluminium frame and the glass, which might result in damaging the PV laminate during frame removal. Therefore, another topic to improve the recyclability of PV modules is development of novel edge sealant solutions that allow an easy removal of the aluminium frame without damaging the PV laminate. In this paper we describe use of alternative easy-to-remove edge sealant solutions as applied to test samples relevant for foil-based back-contact PV technology.

2 EXPERIMENTAL

2.1 Alternative edge sealants

The first step in any recycling process is removal of aluminium frame. In state-of-the-art PV modules this is done manually with the risk of distorting the aluminium frame and damaging the glass due to the high bonding strength of traditional edge sealants. PV 508 from Dow Corning or Duplomont 918 double sided adhesive tape are examples of standard edge sealing solutions. Alternative edge sealants were evaluated by testing their ability to limit moisture/oxygen ingress for small-size samples. The tested samples represent a foil-based back-contact module design developed at ECN. A schematic view of a foil-based back-contact PV module is shown in Figure 1. Standard EVA encapsulant was applied in thes test samples.

The conductive copper foil integrated in the back sheet is sensitive to presence of oxidizing agents and moisture and therefore a good monitor for the effectiveness of the edge sealing. Sealing solutions based on use of U-profile rubber, ‘O’-ring, sponge rubber and single-side adhesive tape were tested in especially-designed frames as shown in Figure 2.

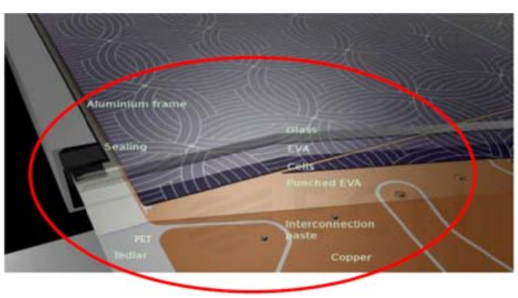

Figure 1: A cross-section of a foil-based metal wrap through (MWT) PV module

As reference the Duplomont 918 double sided adhesive tape was used as edge sealant. The produced test-coupons were tested in line with IEC 61215 for 1000 hours under damp heat (DH) condition.

2.2 Alternative encapsulant (TPO instead of EVA)

Second step in recycling is the separation of the laminate components, such as glass, solar cell, copper (sheet in case of back-contact cells, or tabs for H-pattern modules) and backsheet. Adaption of an recycling-friendly encapsulant material, like TPO is beneficial in that respect.

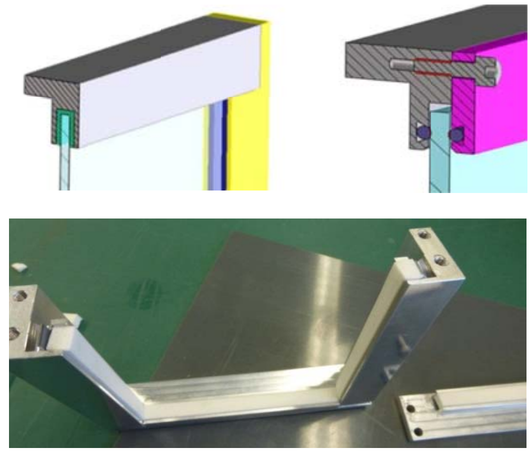

Figure 2: Top: schematic view of sample design to test alternative edge sealants (left: U-profile rubber; right: “O”-ring); below: photograph of set-up for testing sponge rubber

At the same time reliability of TPO-based modules has to be demonstrated. First, test coupons (backsheet, encapsulant, glass - without cells) were produced using EVA and TPO encapsulants and tested under DH conditions (2000 hours). Discolouration of the copper layer indicates the sealing properties of the encapsulant in the PV module. Second, full-size MWT-modules were produced using EVA and TPO and tested according to IEC 61215 under DH conditions.

2.3 Development of alternative PV module separation technique

At ECN a new method of separating the three components of a PV laminate (glass, solar cell and conductive backsheet) is under development. In this research foil-based single-cell metal-wrap-through (MWT) back-contact modules were produced using EVA and thermoplastics as encapsulant, (see Figure 1). In MWT modules the thickness of the encapsulant between glass and solar cell is 200 micron.

The separation of the PV module components was executed in two stages. Firstly, at temperatures were the thermoplastic material starts to soften, the back sheet can be pulled from the PV module. Secondly, at temperature further increased to values were the thermoplastic is highly viscous but does not start to decompose. At this temperature, the encapsulant between the glass and solar cell was separated by cutting between the solar cell and glass with a wire saw, as shown in Figure 3, resulting in glass and solar cells coated with encapsulant residue. The wire saw can operate at varying sawing frequency and a force of several hundreds of Newton can be applied. The diameter of the wire was 0.3 mm.

Methods to clean the glass mechanically at room temperature are available. Manual rubbing the glass with a stainless steel brush results in a clean glass surface without scratches visible on the glass. In addition of ethanol or isopropyl alcohol the process of removing the encapsulant residues can be speed up significantly. Optimizing and scale up this cleaning process of the glass sheet is under development.

The solar cells can be cleaned by pyrolysis at a temperature around 450°C. The advantage of this method

Figure 3: Photo of the wire saw set-up used to separate the solar cell from the glass by cutting through the thermoplastics-based encapsulant

is that the required energy to clean the solar cell can be reduced because the heating of the glass plate, which consumes a lot of energy, is avoided. A second advantage is the increased surface area of the encapsulant residues on the solar cell, which may facilitate the removal of the combustion products otherwise enclosed between the solar cell and glass sheet. The breakage of solar cells is/should therefore be strongly reduced. We are currently evaluating and quantifying the possible benefits of this wire sawing approach over simple pyrolysis of the complete laminate.

3 RESULTS AND DISCUSSION

3.1 Alternative edge sealants

The samples with alternative edge sealants were tested for 1000 hours in damp-heat. Standard EVA encapsulant was applied in this experiment because as mentions in chapter 3.2 the EVA encapsulant is more sensitive for air leakage than TPO encapsulant. The levels of discoloration of the copper layer in the back-contact foil for some tested alternative edge sealants are shown in Figure 4. These results indicate that when using no edge sealant a circular discolouration is visible on the copper layer. Using alternative edge sealants, like "O"-ring or sponge rubber, less pronounced discoloration of the copper layer compared to the application of double-sided tape is visible. Application of single-sided adhesive tape (bonding only to the glass and backsheet) results in comparable discoloration of the copper layer as when using double-side adhesive tape. The best performing alternative edge sealant is U-profile rubber, for which almost no discolouration of the copper is visible. For these alternative sealants, due to absence of adhesion to the glass or aluminium frame, both module components can be separated from one another very easily without distortion of the aluminium frame or breakage of the glass sheet.

3.2 Alternative encapsulant (TPO instead of EVA)

Test coupons relevant for back-contact modules, with glass – encapsulant (EVA or TPO) – back contact foil (TPC 3480 from Isovoltaic AG), were produced. The peel strength was measured at t-zero. The samples were aged in climate chamber (1000 hours damp-heat or 200 thermal cycles). In Table I the observed changes in peel strength after climate chamber test are shown. From these results it is seen that the peel strength of EVA after climate chamber test decreases after DH and only slightly after TC test. For TPO the peel strength seems to increase during climate chamber test.

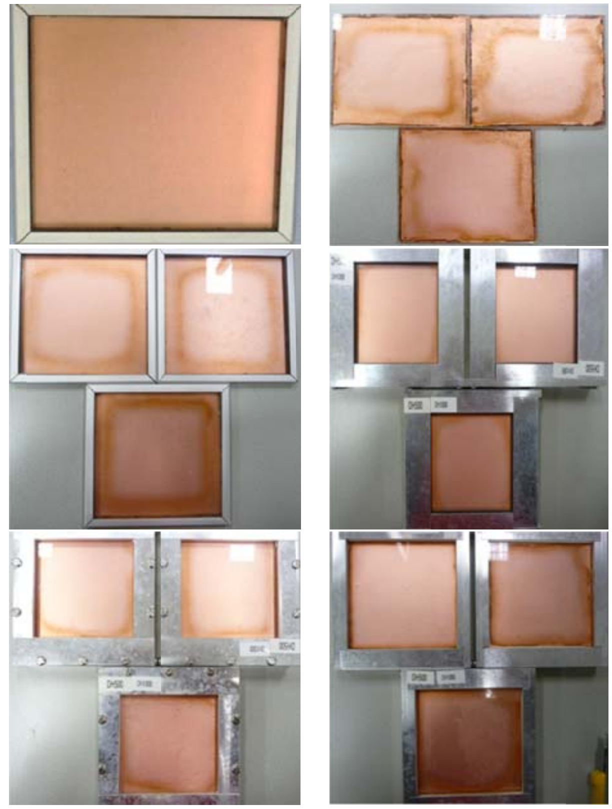

Figure 4: Visual appearance of tested coupons with alternative edge sealants after 1000 hours in DH. Upper left: sample before DH test. Upper right: without edge sealant. Middle right: double side adhesive tape (reference). Middle right: U-profile. Below left: "O"-ring and below right: sponge rubber

The adhesion between encapsulant and the copper layer in the conductive back sheet is the weakest interface.

Table I: Changes in peel strength during climate chamber test of 1-cell size test-coupons

encapsulant	Peel strength (N/cm)				
	t zero	DH 500	DH 1000	TC 100	TC 200
EVA	60	20	5	45	50
TPO	130	170	>>100	140	155

Visual inspection of these test coupons showed that in samples with EVA the circular discoloration zone on the copper foil was observed, but hardly any discoloration for TPO-based sample (see Figure 5).

Full size back-contact modules (60 cells) were produced using EVA and TPO and tested for 2000 hrs in DH (that is 2x IEC61215 test). In Figure 6 the change in fill factor and power loss during DH test are presented. These results demonstrate that modules with TPO encapsulant show improved reliability under DH conditions as compared to modules fabricated with EVA. The decrease in power is for almost 50% caused by decrease in fill factor.

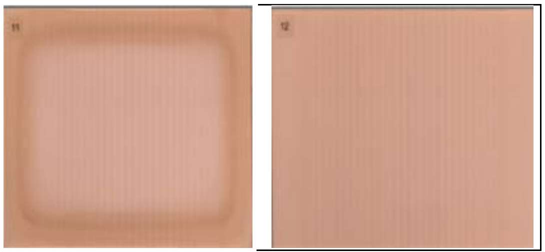
Figure 5: Two test-coupons with encapsulant EVA (left) and TPO (right) tested for 1000 hours in DH

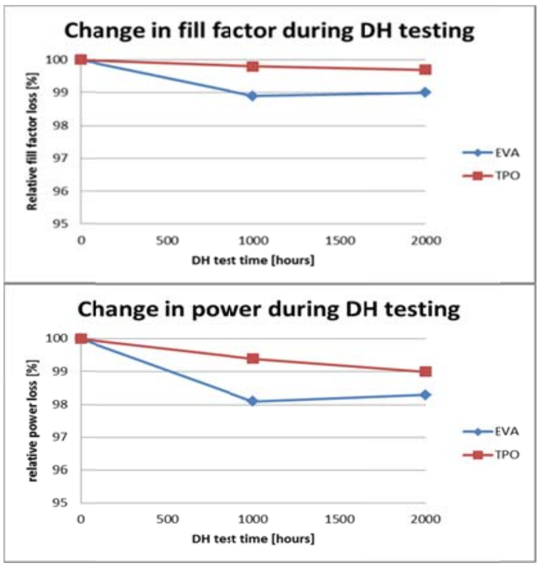

Figure 6: Changes in fill factor (upper) or power (lower) during 2000 hour DH test

3.3 Development of alternative PV module separation technique

Single-cell MWT PV modules with TPO encapsulant were placed on a hotplate with temperature set at 120°C. After temperature stabilisation a starting separation at the edge of the module was made by a blunt knife. By pulling on this starting point the conductive backsheet could be easily removed. A large amount of encapsulant remains on the Cu surface of the conductive back sheet (see Figure 7).


Figure 7: Overview of the removal of conductive backsheet from module, in which thermoplastic as encapsulant was applied

The temperature was then further increased to values between 150-200°C. The wire was pressed against glass into the molten highly viscous encapsulant. With a saw frequency of 5-10 Hz and force on the wire of 100-200 N the wire cut the encapsulant between the solar cell and glass. Under these conditions it took about 1 minute to separate a solar cell from the glass sheet, resulting in a completely separated unbroken solar cell and glass sheet, though both covered with encapsulant(see Figure 8).


Figure 8: Separating solar cell from glass sheet for thermoplastic-based module. The separated cell is shown on the right

Increasing the temperature decreased the viscosity of the encapsulant, but had no influence on the separation speed. At temperatures above 200°C the thermoplastic encapsulant began to decompose.

4 CONCLUSIONS

We have investigated new approaches to enhance recovery of valuable materials during the recycling of crystalline Si (cSi) PV modules.

Alternative easily removable edge sealants can result in a good edge sealing of laminates with low air and/or moisture ingress. Edge sealing by U-profile, "O"-ring and sponge rubber result in hardly any copper foil discoloration as compared with no edge sealant. The observed Cu discoloration was even less noticeable than with application of the reference double side adhesive tape from Duplomont (Duplomont®918). These alternative sealants can benefit speed and quality of module recycling.

TPO was tested as alternative encapsulant to allow new methods of separation of the laminate components. The reliability of the TPO-based PV modules is comparable or even better than the reliability of EVA-based PV modules. Accordingly, for full-size TPO-based back-contact modules, power remained at 99% of the initial value after 2000 hrs exposure in DH (IEC61215), whereas full-size EVA-based modules tested under the same conditions retained 98% of the original value. It appears that the resistance against oxygen and moisture ingress in a module is better for TPO-based modules than for modules in which EVA is applied as encapsulant.

A newly-developed wire saw method that allows separating entire solar cells from glass has been demonstrated on 1-cell modules with TPO encapsulant. It is possible to achieve complete separation of backsheet, intact solar cells, and glass sheets, albeit both contaminated with thermoplastic. The glass sheet can be mechanically cleaned (under development) and the encapsulant from the solar cell can be removed at 450°C. We are investigating the possibilities for scaling up in size and speed, and the benefits over simple pyrolysis of the complete laminate.

5 ACKNOWLEDGEMENTS

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