LOW-STRESS INTERCONNECTION OF SOLAR CELLS

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ABSTRACT

The suitability of a snap-curable acrylic-based conductive adhesive as a low-stress interconnection for thin solar cells was studied. Modules were manufactured using the conductive adhesive with industrial thin crystalline silicon solar cells. The best results were obtained for an adhesive with a high silver filler content. The adhesive resulted in a similar peel strength to a soldered interconnection. Although the contact resistance of the adhesive is much higher than for solder, it does not affect the module output power. Degradation in fill factor of only 2 % was measured after 1000 thermal shock cycles while no degradation was observed at all after 1000 hours damp-heat. Further testing on full-size modules to prove the suitability of the conductive adhesive in outdoor use is ongoing. Climate chamber test results of a direct comparison with soldered modules are presented.
Keywords: PV modules, conductive adhesive, module manufacturing

1. INTRODUCTION

Due to the reduction in thickness of wafers and the increased cell size, which requires thicker tabs to cope with the increased current, the stresses at the interconnections are becoming more critical. Soldering of the tabs to the cells results in a rigid interconnection and residual stresses due to thermal expansion coefficient mismatch between silicon and the solder. During service, the temperature cycles seen by the interconnection will result in damage to the silicon [1]. The interconnection will result in (micro-) cracking of silicon and eventually pull-out of silicon from the cell. This will be seen in a decreasing module efficiency and ultimately failure. Alternatively, cracks can develop in the solder itself resulting in an increase in electrical resistance through the interconnection [2].

To be able to make modules using thin cells with a large surface area, a low-stress interconnection technology needs to be developed which can guarantee reliable operation of the module for a period equivalent to that for a traditional soldered module with the same power output. A suitable candidate for the replacement of solder is conductive adhesive [3]. The lower processing temperature of these adhesives, as compared to soldering, results in a lower residual stress after cooling to room temperature. Conventional lead-containing soldering occurs at temperatures around 220ºC, whereas conductive adhesives can be cured at temperatures well below 150ºC. Conductive adhesives also have the advantage over traditional solders of being lead-free.

The adhesive can be epoxy, acrylic or silicone with the conductive component provided by silver flakes added at between 75 and 85 % by weight. During curing of the adhesive, the silver flakes are forced into contact with each other providing a conduction path through the adhesive [4]. The choice of adhesive is determined in part by the processing necessary for curing. Ideally a system is needed which requires a minimum of adaptation of the cells and manufacturing processes used for soldering. Curing of the adhesive can take place during lamination or can be implemented as part of a tabber-stringer with curing by a heat source such as infrared lamps (see Figure 1).

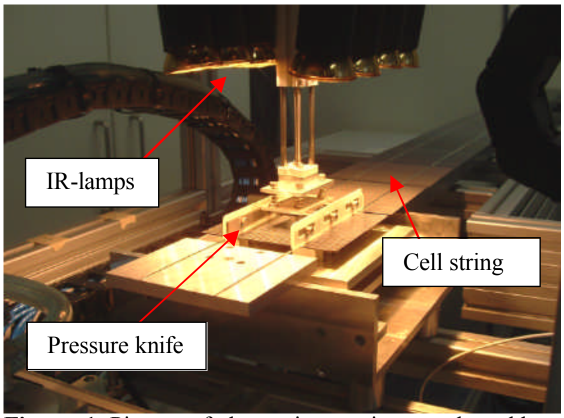

Figure 1 Picture of the curing station on the tabber-stringer for conductive adhesives. Pressure is applied to the tab by a ceramic knife. Adhesive is cured by IR-lamps above the string. Transfer of cells and string as well as application of adhesive is automated

To be a successful replacement for solder, the conductive adhesive has to meet a number of criteria. Any increase in resistance of the interconnection must be minimised so that the power output of a module made with conductive adhesive is similar to that for a soldered module. The mechanical strength of the interconnection must remain sufficient to allow manipulation for further processing and to be able to survive possible stresses imposed during service life of the module. The interconnection must be able to survive testing protocols (e.g. IEC 61215) without significant loss of module power output. The adhesive must also be available in a form that allows efficient processing when making the module.

2. SNAP-CURABLE CONDUCTIVE ADHESIVE

In this work a snap-curable conductive acrylic adhesive was developed as a replacement for soldering in module production. The adhesive has a short curing time of only 2 seconds and a curing temperature of 120-150ºC; significantly lower than soldering. Using this adhesive, curing can be performed by IR lamps with the lamp intensity and processing temperature controlled by a pyrometer.

To determine the mechanical properties of an interconnection made with the adhesive, tabs were attached to busbars on H-pattern cells and subsequently removed during a peel test. The average force needed to remove the tab was compared with the force required to remove a soldered tab, with the tab dimensions and cell type remaining constant. The results of these experiments showed that the mechanical strength of the interconnection using the conductive adhesive was similar to that of the soldered tab (1.9 ± 0.1 and 2.0 ± 0.9 N/mm respectively). The removal force showed less variability for the conductive adhesive. Analysis of the cell after removal of the tab showed that the conductive adhesive fails in cohesion with adhesive present on both the cell and the tab after testing. The soldered tab failed by pull-out of silicon from the cell.

The electrical properties of conductive adhesives are known to be inferior to those of soldered interconnections. The contact resistance of conductive adhesive with 75 % filler content on crystalline silicon cells with screen-printed and fired contacts varied between 10 and 40 $m\Omega.mm^2$. This is high enough to have a noticeable affect on the module fill-factor. In comparison, soldered interconnections have a contact resistance typically two orders of magnitude lower. In addition, the contact resistance was found to be pressure sensitive and inconsistent. This was observed after the interconnection of cells into strings. Post-curing of the interconnection at 150ºC for 10-30 minutes showed no improvement. After lamination of single-cell modules the contact resistance was more consistent with fill-factors of above 70%. A number of these laminates were subjected to climate tests (500 cycles of thermal cycling, 1000 hours of UV and testing in the field) with no degradation observed. It was concluded that the performance of this adhesive only just met the requirements of the interconnection.

To improve the consistency of the contact resistance and to eliminate the pressure sensitivity, the silver filler content of the adhesive was increased to 85 %. Contact resistance was measured using the transition line method (TLM). The adapted adhesive had a contact resistance of 9 $m\Omega.mm^2$ on screen-printed and fired contacts, with no pressure sensitivity and with no change seen in this value after lamination. A peel test showed that the modification of the adhesive had no affect on the mechanical properties of the interconnection.

3. FURTHER TESTING OF ACRYLIC ADHESIVE VARIATIONS

To test the suitability of the adhesive for low stress interconnection, a number of single-cell laminates were made with variations of filler content in the adhesive and tested in thermal shock and damp-heat. Variations included the addition of two metal additives to the low and medium filler content adhesive. The thermal shock test involved rapid temperature changes between -40 and 85ºC. Each sample is held at the minimum temperature for 10 minutes, followed by 10 minutes at the maximum temperature. This test can be compared with the IEC61215 thermal cycling test run 10 times faster. The damp-heat test was performed at 85ºC with relative humidity of 85 %. The modules were characterised before testing using a flash tester to determine the fill-factor. This was compared with the fill-factor of the cells used. The modules were measured at predetermined steps during the tests.

After lamination, the best interconnections were seen with the high fill content adhesive. This adhesive results in the lowest average loss in fill-factor between cell and module, with the smallest standard deviation. As seen in earlier experiments, a lower silver filler content gives less consistent results and a larger loss in fill-factor. This is due to there being insufficient silver particles in the adhesive to provide conduction paths through the interconnection. The adhesives containing additives do not appear to improve the interconnections when compared with the high filler content adhesive.

Thermal shock testing shows that the high filler content variant of the adhesive, when applied in sufficient quantity, performs the best of all adhesives tested (see Figure 2). The fill-factor loss at 1000 cycles is within 5% of the starting value. Of the other adhesives, the medium fill and the medium fill adhesive with additive 2 remain within 5 % of their starting fill-factor value, but show greater degradation than high fill adhesive. The other two adhesives drop to below the 5 % limit within approximately 700 cycles of the test.

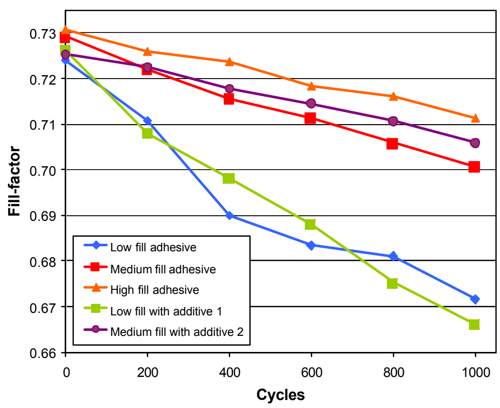

Figure 2 Plot of fill-factor during thermal cycling of variation on adhesive showing that the best performance is achieved with a high fill adhesive with no additive

The damp-heat tests show little degradation in fill-factor for all variation of the acrylic conductive adhesive. Any variation seen would fall within the accuracy margins that can be expected for the characterisation method.

4. FULL SIZE MODULE

Using the high filler content adhesive and the knowledge gained in the experiments described above, full-size modules were made using a dedicated tabber-stringer. The adhesive was cured using infra-red lamps as a heat source with the temperature controlled by a pyrometer. The curing time was set at less than 10 seconds. Tabs and adhesive were automatically applied to increase the reproducibility of the process.

Strings of nine cells were made using multi-crystalline silicon wafers with a thickness of ~200 µm. The cells were screen-printed with a silver H-pattern on the front and a full aluminium rear side with silver contact points. The strings were then used to make modules with four strings to a module, encapsulated with EVA, a PET-PVF foil at the rear and 4 mm low-iron glass at the front. One module was installed in the field with constant monitoring of it performance. After four months the module shows no degradation in power output or fill-factor when compared to the starting values (see Figure 3). The test is still ongoing.

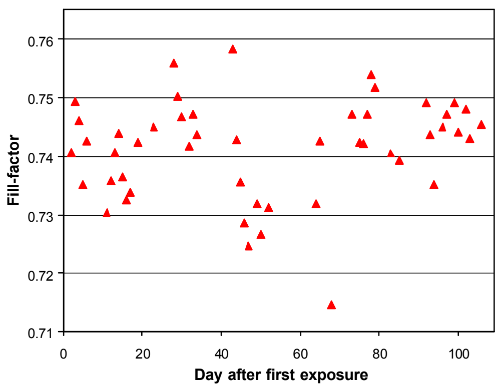

Figure 3 Change in fill-factor for module made with strings manufactured with conductive adhesive installed in the field. The module shows no degradation after four months operation. The test is ongoing.

5. COMPARISON WITH SOLDERED STRINGS

Further strings were manufactured for the industrial partners participating in this research. A number of different cell types were provided with various thicknesses to test the limits of applicability of the adhesive for module manufacture. The strings were manufactured at ECN using the dedicated tabber-stringer with the parameters kept constant. The strings were shipped to the partners, where they were assembled into modules. The modules were then subjected to a number of tests according to IEC61215. These tests were run parallel to tests of modules made with the same cells, but processed using standard soldering procedures. This allowed a direct comparison between the adhesive and soldering technologies. The initial results of these test show that the adhesive performs as good as the solder in almost all cases.

For BP Solar, strings of 9 cells were made with LGBC Saturn cells in two thicknesses: 200 and 300 µm. Modules were made using one string of each type of cell with an equivalent string made by hot-bar soldering giving a module of 4 x 9 cells (see Figure 4). The 36-cell module was constructed to allow separate monitoring of each string.

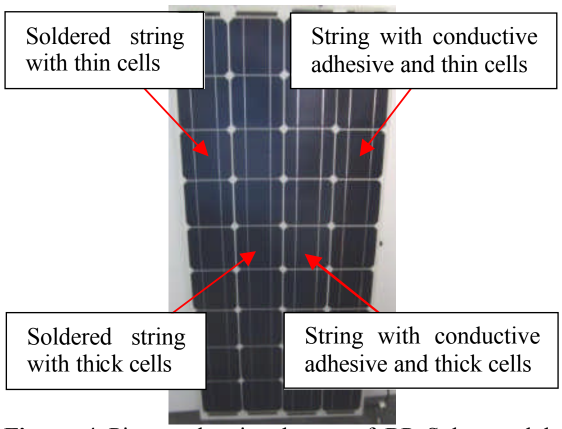

Figure 4 Picture showing layout of BP Solar module with one of each type of string included in a single module. Each string can be monitored. A similar design was used by Isofoton, but with all cells having the same thickness

Two modules were then subjected to thermal cycling for 500 cycles. A further two modules were included in a damp-heat test for 1250 hours. A final module underwent a humidity-freeze test followed by an IR-scan. The thermal cycling and damp-heat results showed that degradation of P_{max} and fill-factor was within 5% of the starting value over the duration of the test (see Figure 5 and Figure 6). The degradation for the modules made with conductive adhesive was similar to that seen for the hot-bar soldered modules. The IR-scan of the humidity-freeze module revealed no broken cells or hot-spots in the strings made with the conductive adhesive. An extra module was made with strings of thin cells interconnected with conductive adhesive. This was subjected to thermal cycling with an applied load of 5 A for 500 cycles. As for the previous experiments, the degradation in P_{max} and fill-factor remained within the 5 % limit. An IR-scan of the module after testing showed no damage or hot-spots.

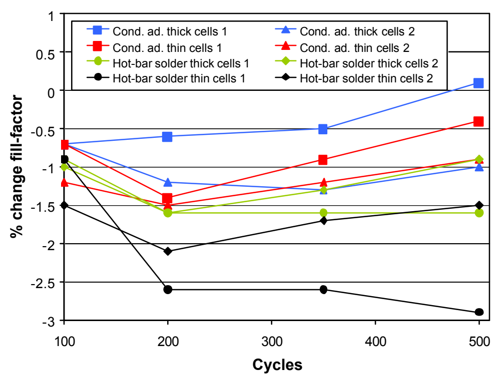

Figure 5 Plot showing the change in fill-factor during thermal cycling of modules containing strings made with thick and thin cells interconnected with conductive adhesive or by hot-bar soldering for cells provided by BP

Solar. The performance of the strings made with conductive adhesive is comparable with those made by soldering.

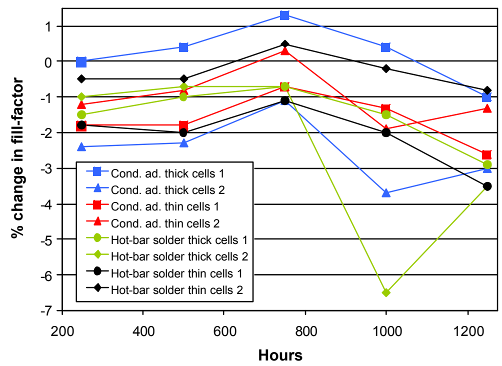

Figure 6 Plot showing the change in fill-factor during damp-heat testing of modules containing strings made with thick and thin cells interconnected with conductive adhesive or by hot-bar soldering for cells provided by BP Solar. As for thermal cycling the strings made with conductive adhesive are comparable with those made by soldering.

For Isofotón, strings of 9 cells were made using mono-crystalline cells with a thickness of ~240 µm. A number of 4 x 9 modules were constructed containing two strings made with conductive adhesive and two strings made with equivalent cells interconnected by soldering. The modules were manufactured to allow measurement of each individual string. The modules were subjected to damp-heat tests, thermal cycling and in-field testing. After 1056 hours, the damp-heat test results showed that degradation of the fill-factor for the strings made with conductive adhesive was well within the 5 % limit (see Figure 7). The performance of the strings made with the conductive adhesive was similar to that seen for the soldered strings. In-field testing showed no degradation after two months of monitoring.

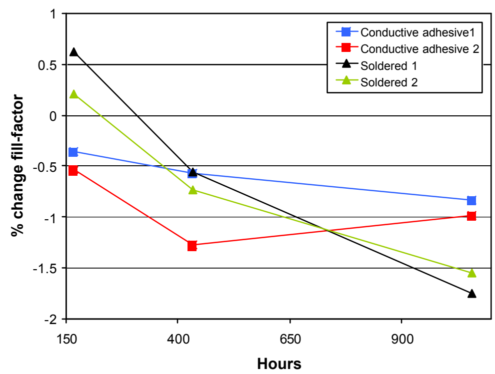

Figure 7 Plot showing change in fill-factor for two strings interconnected with conductive adhesive and two strings interconnected by soldering. The cells were provided by Isofotón with no difference in the cell thickness. It can be seen that the performance of the conductive adhesive is comparable with the soldered strings.

Solar World Industries manufactured a number of 2 x 9 cell modules from the strings made at ECN. The modules contained either thin monocrystalline cells (<180 µm) or standard thickness cells (~240 µm). These were compared with 2 x 9 modules containing soldered standard cells (see Figure 8). In all cases, the modules were constructed to allow assessment of the individual strings.

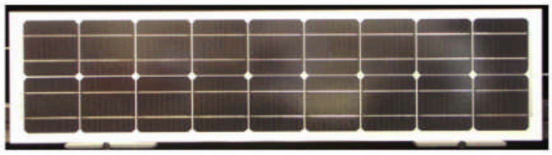

Figure 8 Module constructed by Solar World with two strings of the same configuration (thickness and interconnection method) per module

The modules were subjected to a number of tests including damp-heat and thermal cycling. The results show that for the damp-heat test, all modules remained within 5 % of their starting value for P_{max} and fill-factor. The standard cells made with conductive adhesive showed an increase in P_{max}. The fill-factor for all modules showed little variation after 1000 hours (see Table 1). For thermal cycling, degradation of more than 5 % was seen for the standard cells made with conductive adhesive (see Table 2). The average degradation in fill factor for the two strings contained in one module was 7.7 %. A second module containing similar strings showed a degradation of 3.4 %; within the 5 % limit as defined in IEC61215. Both of the modules containing the thinner cells showed a degradation in fill-factor similar to that seen for the modules containing the soldered strings.

	Damp heat 1000 hours		
	Initial FF	Final FF	Change %
Conductive adhesive			
Thin cells	75.9	76.0	0.1
Standard cells	75.6	76.1	0.3
Soldered			
Standard cells	75.1	74.8	-0.4

Table 1 Data for change in fill factor after damp-heat for 1000 hours comparing thin and standard cells interconnected with conductive adhesive and soldered standard cells. The values given are the average of two strings, which make up one module, with one modules tested for each configuration

	Thermal cycling 200 cycles		
	Initial FF	Final FF	Change %
Conductive adhesive			
Thin cells 1	75.6	74.0	-2.1
Thin cells 2	74.7	73.6	-1.5
Standard cells 1	75.6	73.2	-3.4
Standard cells 2	75.5	73.9	-7.7
Soldered			
Standard cells 1	75.0	73.8	-1.6
Standard cells 2	74.4	73.6	-1.5

Table 2 Data for change in fill factor after thermal cycling for 200 cycles comparing thin and standard cells interconnected with conductive adhesive and soldered standard cells. The values given are the average of two strings, which make up one module, with two modules tested for each configuration

6. CONCLUSIONS

The results presented in this paper show that it is possible to use an acrylic based conductive adhesive as an alternative to soldering. The short curing time of the adhesive is comparable to the time necessary for making soldered interconnections. The electrical performance of the interconnection is comparable to that of a soldered interconnection at module level. The durability of the interconnection has been tested in full-size modules according to the IEC61215 standards and has been found to be as good as for soldered modules using similar cells.

The greater elasticity of interconnections made with conductive adhesive and a lower processing temperature as compared with soldering will allow handling of even thinner cells than used in this work. Manufacturing of modules using cells with thicknesses less than 100 µm is planned to further demonstrate the suitability of conductive adhesives in facilitating the use of such thin cells.

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