Compatibility of copper-electroplated cells with metal wrap-through module materials

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ABSTRACT

As part of the European FP7 R&D project 'Cu-PV', the compatibility of copper-electroplated metal wrap-through (MWT) cells with conductive adhesives has been investigated. The objectives of this project include to reduce, by the use of copper plating, the amount of silver utilized in cell manufacturing, and to demonstrate the compatibility of high-power n-type back-contact module technology with copper-plated cells. The overall goal is to reduce the impact on the environment of cell and module manufacture. MWT module technology as developed by ECN uses conductive adhesive to make the interconnection between cells and a conductive backsheet foil. These adhesives have been proved to result in very reliable modules in the case of cells with fired silver metallization. To determine the compatibility of conductive adhesive with copper-plated cells, component tests were performed, followed by the manufacture of modules with copper-plated cells and conductive adhesive interconnections. Climate chamber testing of these modules showed that the adhesive is compatible with the copper-plated cells. The next steps include further optimization of the plating process and additional testing at the module level.

Introduction

PV modules have an environmental impact, broadly speaking, via the embedded energy and scarcity of PV module material components, as well as an environmental impact in other fields (such as toxicity). The embedded energy is dominated (around 75%) by the silicon wafer (in the case of a crystalline silicon PV module); glass, EVA and the aluminium frame account for most of the remainder. Silver is the scarcest material used in crystalline silicon PV module manufacturing. Although embedded energy has the greatest environmental impact, there are also important contributions from silver, copper, aluminium and glass (Figs. 1 and 2).

The Cu-PV project [1] ('Cradle to cradle sustainable PV modules') is an R&D project in the European Union's Seventh Framework Programme on the topic of improving resource efficiency. It focuses on three key sustainability issues of current PV technology:

1. Reducing the energy demand in PV manufacturing, by developing high-power back-contact solar cell designs that use thinner wafers, i.e. less silicon.
2. Minimizing the use of critical materials, namely silver and lead.
3. Improving the recyclability of PV modules.

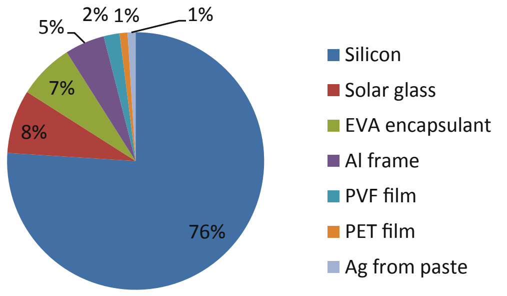

Figure 1. Embedded energy breakdown for a PV module containing crystalline silicon cells.

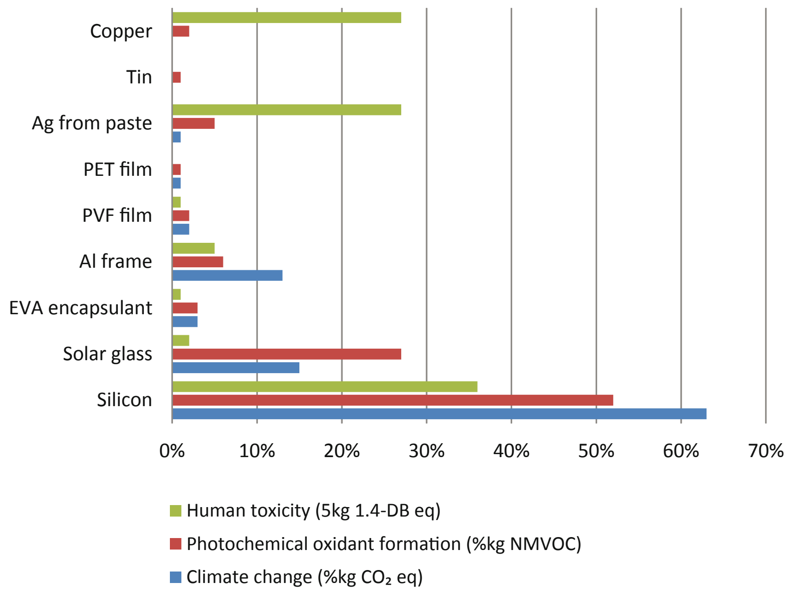

Figure 2. Environmental impact of silicon PV modules in terms of climate change and toxicity.

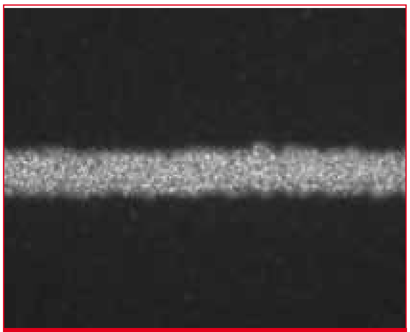

Figure 3. Seed and plated metallization finger with a width of 69µm.

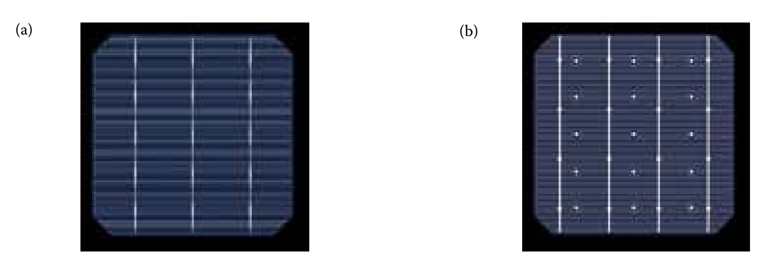

Figure 4. An nMWT cell design: (a) front-side grid; (b) rear-side contacts. The rear-side contacts are shown by the 4 × 4 pattern, and the front-side contacts (connected to the front-side grid through vias in the wafer) are shown by the 3 × 5 pattern.

Although Ag consumption in the manufacturing of solar cells has recently been significantly reduced for cost reasons, its use in solar cell metallization is still unsustainable in the longer term. The world's Ag reserves are sufficient for less than 25 years' mining of this metal at the current rate. Many options have been investigated for switching to non-Ag metallization of solar cells, most prominently physical vapour deposition (for back-contact cells) and copper plating, or a combination thereof.

> "The world's Ag reserves are sufficient for less than 25 years' mining of this metal at the current rate."

To make the transition from present fire-through metallization processes to copper plating as smooth as possible, one of the metallization methods under investigation in the Cu-PV project is seeding with a minimal amount of Ag metallization, followed by nickel–copper electroplating. Screen-printing technology cannot easily yield a significant reduction in Ag consumption for a seed pattern, as it does not have the ability to print very thin and very narrow lines. Thin lines are important for minimizing Ag consumption, whereas narrow lines are important for high efficiency (the Cu plating will widen the lines). In the Cu-PV project Ag seeding is therefore done by inkjet printing, which offers a contact resistance and recombination as good as that obtained using conventional Ag pastes, but with a much lower use of Ag and with significantly narrower lines. Seed patterns using 12mg Ag have so far been demonstrated, with 40µm-wide lines that could be electroplated without problems. A particular advantage is that bleeding of the seed lines is small, so that the plated lines do not contain much parasitic plated material at the edges (Fig. 3).

The current focus of the Cu-PV project is on high-efficiency n-type MWT cells [2, 3], with emitter contacts on the rear of the cell (Fig. 4). This means that rear-side junction isolation will be the centre of attention.

The first module tests in the project, however, as reported in this paper, were carried out on plated non-metal-wrap-through cells. Also, the seed grids in these first tests were made by screen printing rather than by inkjet printing (Fig. 5).

MWT module technology

MWT module technology as developed by ECN [5,6] makes use of a conductive backsheet foil in combination with a conductive adhesive, in contrast to the tabbing and stringing process used with H-pattern cells and modules. The conductive backsheet foil is made up of a copper–PET–PVF laminate, with the copper patterned to match the contact pattern on the rear of the cells. The conductive adhesive is chosen to have the correct printability, curing properties, and conductivity and flexibility after curing.

Manufacture is performed using a module line as developed by Eurotron. In this production line, the conductive foil is placed on a vacuum carrier, after which the conductive adhesive is stencil printed onto the foil at the position of the contact points on the cells. A layer of EVA is placed on the conductive backsheet foil. The EVA is perforated with holes at the positions of the conductive adhesive dots to ensure contact between the conductive adhesive and the cells. The cells are then arranged one by one on the conductive backsheet, with the cell only being touched once during the whole process. A second layer of encapsulant is then placed on the cells, followed by a glass sheet. This top layer of encapsulant is locally heated to tack the cells to the glass in order to prevent movement during lamination.

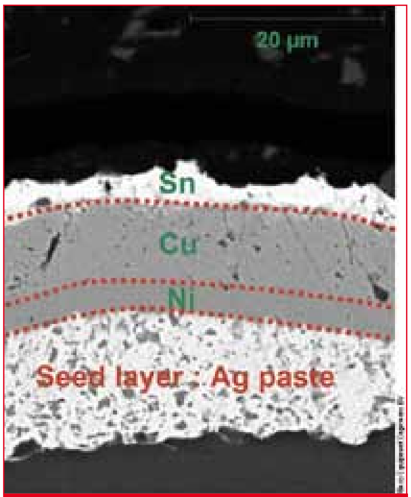

Figure 5. Seed and plate structure of the metallization as tested in this study [4]. The final layer was tin, silver or an organic solderability preservative (OSP). The OSP is also used on the conductive backsheet foils and so is known to be compatible with processing using conductive adhesive.

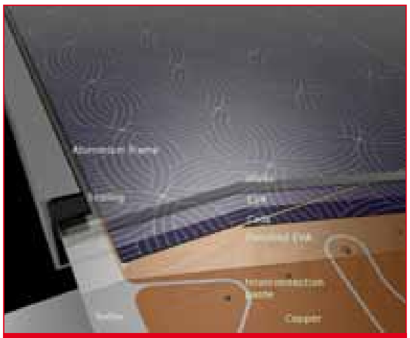

Figure 6. Cross section through an MWT module, showing the conductive backsheet with patterned metal layer, conductive adhesive dots (interconnection paste), the first sheet of EVA, MWT cells and other module materials.

The module stack is then inverted for the lamination process. During lamination, the encapsulant and adhesive are cured in a combined lamination and interconnection step.

There is no local heating as with soldering: the whole module is heated uniformly and the temperature is limited to the curing temperature of the adhesive and encapsulant (i.e. 150°C). This makes the process ideal for very thin cells as investigated in the Cu-PV project. A cross section of an MWT module is shown in Fig. 6.

Module manufacture with no cell breakage has been demonstrated in other projects [7,8] using cells with a thickness of less than 120µm. Climate chamber testing has been performed on MWT modules, resulting in less than 2% degradation in power output after 400 thermal cycles and 2000 hours of damp heat for cells with fired silver metallization and EVA as the encapsulant. With a thermoplastic encapsulant, a degradation of less than 1% in power output for the same test has been measured [9]. A number of production lines have been sold to module manufacturers, and commercial production of this type of module is expected to begin before the end of 2013. In this study, the suitability of the module technology and materials, particularly the conductive adhesives, in combination with copper-plated cells is investigated.

Component testing

The first stage in evaluating the compatibility of copper-plated cells with MWT module technology was to measure the contact resistance and adhesion strength between the adhesive and the copper plating on the cells and to compare this with the values for a cell with fired silver contacts. It is known that the adhesive in combination with a cell with fired silver metallization has a contact resistance low enough not to be dominant in the module performance, and an adhesion strength high enough to be able to survive module manufacture and thermal cycling up to 400 hours with limited degradation as mentioned above.

Contact resistance was measured using a transmission line method (TLM). A number of tin-coated copper tabs were stuck to the busbar of a copper-plated p-type cell using a conductive adhesive which had been proven in climate chamber testing with full-size modules. The cells were plated by Meco. A spacer was used between the tab and the cell to simulate the thickness of the EVA and adhesive found in an MWT module between the conductive backsheet foil and the cell. The adhesive dot was printed using a stencil, also with the aim of simulating the shape and volume of adhesive as used in the module. The resistance between the first tab and subsequent tabs was measured and plotted, allowing the contact resistance to be estimated by TLM analysis.

Copper-plating finish	90° peel strength [N]	180° shear strength [N]
OSP	0.5–1	30–40
Tin	0.3–1	21–33
Silver	0.3–1	9–24

Table 1. Peel strength and shear strength results for conductive adhesive contacts on copper-plated cells. The geometry of the adhesive dot in the MWT module makes the 90° peel test unsuitable for the assessment of adhesion strength. The shear test, however, is considered to be more representative of the stresses in an MWT module.

Three types of surface finish were used on the copper of the cell: a silver finish, a tin finish and an organic solderability preservative (OSP). This finish is needed to prevent corrosion of the copper on exposure to ambient conditions, which would result in an increased contact resistance. The contact resistance values of the three types of copper-plated cells were compared with the contact resistance measured for cells with fired silver contacts. The same samples were also used for adhesion testing. Peel testing at 90° was performed first; however, because of the dimension of the adhesive dots and the peel angle, very low values were obtained for the three copper-plated cell types as well as for the cell with fired silver contacts (Table 1). A second series of samples was subjected to a shear test, the results of which allowed the variations in adhesion strength between the different cells to be observed (Table 1). The shear test is considered to be more representative of the stresses seen in an MWT module. These stresses are caused by differences in thermal expansion coefficients between the different module materials and generally act in the plane of the backsheet, resulting in shear forces on the interconnections.

Contact resistance was found to be lowest for the copper-plated cells with a silver coating, followed by the copper-plated cells with a tin coating, and finally the OSP-finished cells. The value for the cells with the fired silver metallization was intermediate between the OSP- and silver-finished copper-plated cells. Despite the higher value, the contact resistance for the OSP-finished cell is nevertheless much lower than the calculated acceptance limit for contact resistance. A contact resistance of this magnitude will not have a noticeable effect on the performance of the module: for example, the contact resistance of the adhesive on an OSP backsheet foil is approximately 500µΩ, and it has also been calculated that this value will not dominate the series resistance in the module (well below 0.1% loss in fill factor). An OSP-finished cell is preferable because of cost and the use of OSP on the conductive backsheet foil. If both cell and foil have the same finish then compatibility with both surfaces can be engineered in one step. The shear test values show that the OSP-finished copper-plated cells have the highest adhesion in shear – higher even than that for the cells with fired silver metallization. This should result in a module that performs well in thermal-cycling tests.

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Pseudo mini-module design and manufacture

After it had been confirmed that the conductive adhesive and copper-plated cells were compatible at the component level, single-cell mini-modules were manufactured for climate chamber testing. Since no copper-plated MWT cells were available at the time, the module design had to be adapted to allow the simulation of the adhesive contact in an MWT module by using an H-pattern cell. The front-side contact was made with tabs soldered to the busbars as for a standard H-pattern cell. The rear-side contacts were formed using a copper-based backsheet with adhesive dots printed on the copper to match the positions of the busbars on the rear of the cell (Fig. 7). Seven dots were printed for each of the three busbars. Holes corresponding to the

Figure 7. Image of a pseudo-MWT mini-module. The front-side interconnection is accomplished by soldering tabs to the busbars; the rear contact to a conductive backsheet is made by a conductive adhesive printed at the location of the busbars on the rear of the cell.

Figure 8. EL image of an H-pattern single-cell module with soldered front-side contact and MWT rear-side contact, showing cracking in the top left corner and finger interruptions at the edges of the cell.

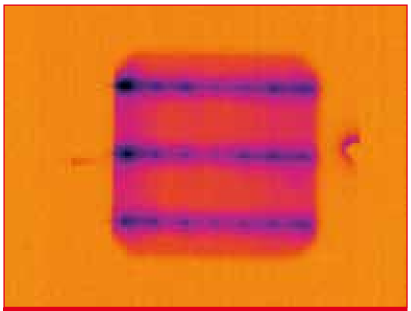

Figure 9. DLIT image of the same mini-module in Fig. 8, showing the position of the conductive adhesive interconnections between the cell and the conductive backsheet foil.

positions of the conductive adhesive dots were punched in an EVA sheet, and the sheet then placed over the dots. The cells were arranged on the EVA so as to make contact with the adhesive dots. A sheet of EVA and a glass plate were placed over the cells, and the stack was laminated to cure both the EVA and the conductive adhesive.

A total of four single-cell modules were manufactured. The performance of the modules was measured using a Pasan 3B flash tester (Table 2). Because of the non-optimized module design, the fill factors (*FF*) of the modules are not particularly high when compared with standard MWT modules, but were considered suitable for climate chamber testing.

Electroluminescence (EL) and thermography (DLIT – dark lock-in thermography) images were generated in order to evaluate the quality of the modules after manufacture. EL images (Fig. 8) reveal some cracking in the cell at the ends of the busbars, as well as finger interruptions on the front of the cell in several places at the edges; this is most likely caused by the soldering of the tabs. Thermography imaging (Fig. 9) shows the position of the conductive adhesive interconnections between the cell and the conductive backsheet foil.

Climate chamber testing

Initial climate chamber testing focused on thermal cycling. The aim of this was to confirm that the adhesion test results obtained during component testing could be translated into good performance. Because of differences in the thermal expansion coefficients of the various module materials, the conductive adhesive contacts between the cells and conductive backsheet foil will

Module code	I_{sc} [A]	V_{oc} [V]	FF [%]	Efficiency [%]
A1535	9.17	0.63	74.4	18.3
A1537	8.95	0.63	74.9	17.8
A1538	9.26	0.63	74.0	18.2
A1540 (control)	9.06	0.63	75.4	18.0

Table 2. *I-V* characteristics of modules manufactured using copper-plated H-pattern cells with MWT interconnections on the rear side and tabbing on the front side (before climate chamber testing).

Module code	ΔI_{sc} [%]	ΔV_{oc} [%]	ΔFF [%]	ΔEfficiency [%]	ΔPower [%]
A1535	0.29	0.93	–1.24	–1.68	–0.03
A1537	0.15	0.89	–0.52	–1.14	–0.51
A1538	0.34	0.90	–2.72	–3.14	–1.52
A1540 (control)	–0.16	1.23	0.80	0.19	1.87

Table 3. Changes in *I-V* characteristics of the modules after 100 thermal cycles, relative to their values at t = 0.

Module code	ΔI_{sc} [%]	ΔV_{oc} [%]	ΔFF [%]	ΔEfficiency [%]	ΔPower [%]
A1535	0.33	0.79	–2.46	–3.00	–1.37
A1537	1.05	0.57	0.48	0.43	2.11
A1538	4.54	0.91	–4.41	–0.82	0.84
A1540 (control)	–0.99	0.64	1.65	–0.37	1.30

Table 4. Changes in *I-V* characteristics of the modules after 200 thermal cycles, relative to their values at t = 0.

be stressed. Any degradation in the power output and fill factor of the module can be related to a loss of contact of the conductive adhesive with either the cell or the conductive backsheet.

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The thermal-cycling test is based on the test included in the IEC 61215 standard and is performed using a current corresponding to the applied I_{mpp}. This subjects the module to more stress in the form of additional heating, especially in areas of high resistivity, such as a failing contact. The total test time was 200 thermal cycles, but testing was interrupted at 100 cycles to allow characterization of the module, so that any degradation could be measured. Characterization of the module was performed by IV flash testing and EL and DLIT imaging, as was also done at t = 0. A total of three modules were subjected to this test, with one control module kept out of the climate chamber.

As seen in Table 3, a maximum of 1.5% reduction in power output was measured for one of the modules (A1538) after 100 thermal cycles. The other two modules showed smaller changes in power output. The reduction in power output for module A1538 could be accounted for by the 2.7% reduction in *FF*. EL and DLIT images (Figs. 10 and 11) of these modules show very little differences from the images made at t = 0. This shows that the interconnections and cells remained stable up to this point.

Table 4 shows that module A1537, showing a power loss after 100 cycles, now shows a power increase after 200 thermal cycles; moreover, the *FF* also no longer shows a decrease relative to the measurement at t = 0. One of the other modules (A1535) shows a loss of 1.4%; this can again be attributed to a 2.4% decrease in *FF*. The third module (A1538) shows no loss in power output, but does show a 4.4% reduction in fill-factor. As was the case for the measurements after 100 cycles, the EL and DLIT images are stable when compared with the images at t = 0, with no hot spots or areas not contributing to current generation.

Figure 10. EL image of a single-cell module after 100 thermal cycles, showing little change relative to the module at t = 0. The module shows uniform illumination, indicating that the cell and interconnections are intact.

The results show that, for the limited sample size tested in this experiment, interconnection between a copper-plated cell and a conductive backsheet gives rise to a reliable module. Some variation in power output was measured, but this was well within the limits as specified in IEC 61215 and was no larger than the variations seen in the control module. For module A1538, an *FF* loss of 4.4% was measured, which was close to the acceptable limit of 5%; no power loss, however, was measured, indicating that, in combination with the high current, the *FF* value may have been a measurement artefact. To determine whether this loss is significant or the result of a manufacturing or measurement error, the number of test samples would have to be expanded and the tests continued to 400 or 600 cycles.

Conclusions and further work

The component testing and climate chamber testing of the mini-modules shows that copper-plated cells are compatible with the MWT module concept and materials. In particular, the cells are compatible with contacting using a conductive adhesive. The contact resistance is similar to that seen in cells with fired silver metallization, as is the mechanical strength of the contact. In mini-modules the initial performance shows that a well-performing module can be produced using copper-plated cells.

“Testing of the mini-modules shows that copper-plated cells are compatible with the MWT module concept and materials.”

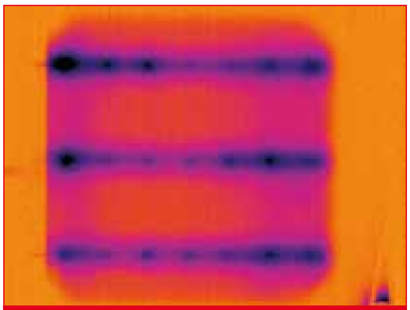

Figure 11. DLIT image of the same mini-module in Fig. 10, showing all contacts to the conductive backsheet foil intact, with little differences from the t = 0 image.

Thermal cycling to 200 cycles demonstrates little degradation in power output, comparable to the thermal-cycling results for an MWT module with cells having fired silver contacts. This shows that it is possible to manufacture reliable MWT modules with copper-plated cells in combination with a conductive adhesive and conductive backsheet foil.

Further work in the Cu-PV project will focus on the development of a high-power copper-plated n-type MWT cell and module. This will not only allow a direct comparison of copper-plated MWT cells and standard MWT cells (with fired silver metallization) and modules, but will also eliminate any negative effects of soldering tabs to the front side of the cell, a procedure that was necessary in the work discussed in this paper. The resulting modules will be subjected to additional climate chamber tests, including further thermal cycling and damp heat, as well as other tests stipulated in IEC 61215. Further work in the Cu-PV project in general will also focus on n-type copper-plated back-junction back-contact cells and modules, the reduction of the wafer thickness, and the evaluation and development of recycling strategies for PV modules.

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Ian Bennett is a researcher at ECN Solar and received a Ph.D. in materials science from the University of Bath. He has been working at ECN since 2006 as a member of the module technology and application group, where he has been involved in the development of MWT module technology and the application of new and novel module materials and module designs.

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Carol Olson received a Ph.D. in physics from Imperial College, London, in 2003. After joining ECN in 2006, she carried out research in the areas of thin-film PV and characterization of silicon solar cells. Dr. Olson currently manages projects relating to life cycle assessment of photovoltaic products and processing lines, as well as those relating to sustainability of PV. She participates in the EPIA sustainability working group and in the IEA-PVPS Task 12 on PV environmental health and safety activities.

Maurice Goris is a chemical engineer and has worked at ECN since 1985. He has over 15 years’ experience in research fields related to solar energy. For the past two years he has worked as a back-contact foil specialist on projects involving module cost reduction and alternative connection methods between MWT solar cells and back-contact foils.

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