4th International Conference on Silicon Photovoltaics, SiliconPV 2014

Investigations of different soldering failure modes and their impact on module reliability

Matthias Heimann*, Ronny Bakowskie, Matthias Köhler, Jens Hirsch, Matthias Junghänel, Alexander Hussack, Steffen Sachert

Hanwha Q-Cells, Sonnenallee 17 -21, 06766 Bitterfeld-Wolfen, Germany

Abstract

Future Photovoltaic is being increasingly forced to reduce costs and increase module power by constant or better module reliability [1]. So over the last years a radical decrease of module prices is observed on the contrary the module power changes to higher classes. This indicates that the common used materials (e.g. frames, solder ribbon, wafer, metallization etc.) join their physical limits. This contains different challenges due to reliability. For future applications such requirements will be e.g.:

- Smaller frames vs. high loads
- Thinner glass substrates vs high impacts
- Smaller interconnection area vs. higher current density and higher thermal dissipation
- Smaller ribbons vs higher cell breakage rate & higher soldering challenges

This represents only a small number of the challenges facing the Photovoltaic industry in the future. The aim and role of PV industry is to realize efficient and reliable modules. This paper will present detailed data on soldering failure modes during string assembly and reliability testing, and the long-term mechanical and electrical stability of the solder joints and their impact on the long-term efficiency of the modules. The data will show that different failure modes have different effects on the quality of interconnections as well as on the reliability of the modules.

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Peer-review under responsibility of the scientific committee of the SiliconPV 2014 conference

Keywords: reliability, soldering, simulation, failure mode

* Corresponding author.
E-mail address: m.heimann@q-cells.com
1. Introduction

Future Photovoltaic will be faced with apparent trends. On the one hand the market is asking for higher module power classes and longer warranty equivalent to higher long term stability, and on the other hand a radical decrease of module prices is expected. So the PV industry is being increasingly forced to get higher efficiencies and reduce costs. So the requirements of the common used material gets tougher due to their physical properties.

In case of soldering for example levelling down the paste consumption and increasing the cell efficiency with several approaches on cell level, will leading to higher current density and heat dissipation at the interconnection area. Due to several degradation mechanisms e.g. crack growth caused by different coefficient of thermal expansion or electro migration, the impact on reliability of such interconnections gets more and more important for long term stability of photovoltaic modules. Otherwise it also important to know which failure mode has the biggest impact on module power and reliability. For that different questions have to be answered:

- How much soldered area is necessary to get a reliable interconnection?
- Which interconnection has the most impact on module reliability, front contact or rear contact?
- Which wetting behavior of the solder is necessary to get a strong interconnection?

This case study concerns investigations of different soldering failure modes and their impact on processability during production and long term reliability. The used materials are well-aligned with the future need for green PV products (RoHS and REACH guidelines) facing new degradation processes and requirements.

This paper is structured into three parts. The first part describes an experiment with different man-made soldering failure modes and their impact on the power loss during thermal cycling. For these 60-cells-modules were produced and tested at climate chamber tests up to 400 thermal cycles. The second part has a view on simulation results confirmed by experiments concerning the most detrimental failure modes. Their influence on series resistance and efficiency issues has been studied. At the third part some results were shown for an initiated failure mode in production line and their influence on the reliability.

2. Different failure modes and their impact on reliability

For this experiment 6 inch multicrystalline-cells with same efficiency class were used. The grid design on front and backside is shown in Fig. 1. The front layout consists of 3 BB with 12 soldering contacts per busbar. The backside has 18 soldering pads (6 for each busbar). The used metallization materials for front and backside are common used products.

![Fig. 1 Front grid and backside of used cells](image-url)
Then the cells were soldered to strings for module assembly. For this study 4 different failure modes were realized and compared to the reference with perfect solder joints. All other module materials (frames, EVA, back sheet etc.) were not changed from standard bill of material for module production. Table 1 described the failure modes of the modules (3 modules per batch) in detail. For Batch 2 only 3 out of 12 front side contact of the cells for each busbar were soldered. Batch 3 has only 1 out of 6 Pads per busbar on the rear side connected to the strings of the solar cells. The “non-contacted-area” where realized with special temperature stable and non-conductive tape. For Batch 2 the contacts were at the edge and in the middle of the busbar for batch 3 only one of the middle pads was contacted.

Modifying the soldering parameter in standard process window for Batch 4 and 5 it was possible to initiate two other failure modes for rear and front side. Failure mode “black mode” can be initiated with very high soldering temperature. In that case the weakest point of the whole interconnection area is the interface between the metallization and the silicon surface with a peel force lower than 1 N/mm.

Table 1. batch overview modules

<table>
<thead>
<tr>
<th>Batch</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batch 1</td>
<td>reference</td>
</tr>
<tr>
<td>Batch 2</td>
<td>3 out of 12 front side contacts soldered</td>
</tr>
<tr>
<td>Batch 3</td>
<td>1 out of 6 rear side pads soldered</td>
</tr>
<tr>
<td>Batch 4</td>
<td>Low wetting of rear side pads</td>
</tr>
<tr>
<td>Batch 5</td>
<td>Black mode front side (high soldering temperature)</td>
</tr>
</tbody>
</table>

Different environmental conditions might be critical for the technical reliability of such failure modes, so these modules where tested according to IEC 61215 in thermal cycling for 400 cycles The IEC criteria is 5 % power loss after 200 cycles. The internal tests are still ongoing until TC600 (VDE quality tested). The evaluation criteria were the electrical parameters.

The results are show in Fig. 2. It is obvious that the different failure modes have different impact on long term reliability. As expected the reference shows the lowest degradation of all tested modules.

Also the front side failure modes (only 3 contacts per busbar) show a marginal influence due to power loss after 400 cycles in thermal cycling. Guessing that a small contact area on front side is enough, handling during module production has to be considered and guarantied. So from that point of view soldering is still a suitable technology to ensure a reliable interconnection. The most impact on module reliability comes from the failure mode initiated on the rear side. Low wetting and cells with only 1 contact per busbar shows the highest degradation on module level. Especially the modules for Batch 3 show the highest power loss.
These modules (1 out of 6 pads on the rear side are soldered per bus busbar) revealing the most detrimental impact in the thermal cycling test a lower encapsulation effect for this batch was also observed in initial stage. Thus the electrical resistance between ribbon and metallization depends to a large extent on the contact area between ribbon and Ag-pad.

However on the rear side the Al metallization is printed higher than the Ag-pads. Therefore there is a gap between ribbon and pad which increases the contact resistance if the solder ribbon is placed incorrect while production.

After thermal cycling a strong impact on power is obvious. One indication is shown in EL-images (Fig. 3). The cracks at initial stage are due to dynamical load testing before the thermal cycle test. The images became shadowing after thermal cycling caused by the degradation of the interconnection of ribbon and cell contacts as well as cell cracking. These facts lead to a power loss up to nearly 20%. From these results it is obvious that the rear side solder interconnections has the biggest influence on module reliability.

In the following the main 2 failure mode are described in detail under different point of views.
3. Simulation of module power losses due to different failure modes

For theoretical calculation of module power losses due to failure contacts, four different scenarios had been investigated. The theoretical results are compared to experimental data. For this experiment, twenty 1-cell modules are being assembled out of standard 6 inch multi- and monocrystalline cells. Aim of the module test is, to show possible influence of thermal cycling while having methodical failure due to soldering process. To prevent any pressure contact on cell level, the solder contacts are covered with isolating material before soldering, like it is shown in Fig. 4a. The reason for this is the expectation, that liquid EVA can possibly cover unsoldered contacts. Due to this fact, any pressure contact after lamination could be prevented and worst case scenario is tested. So every cell in every module is affected with a known specific failure mode.

![Fig. 4](image)

These twenty single--cell-modules are measured afterwards to compare the theoretical calculated data with the reference module with perfect solder joints (Fig. 4b). Here as an example for a failure mode with strong impact on reliability batch scenario will be described as depicted in chapter 2.

The power loss due to one failure contact per busbar is very low for both cell types. The module power degradation will increase exponentially by increase of failure soldering contact number per busbar when every cell is affected with this failure type. The comparison of experimental data with calculated data shows same power loss level compared to complete soldered backside busbars for each cell types [2]. To prevent failure contact scenario in module, it is necessary to use several kinds of analysis tools, like EL imaging and series resistance measurement. If you compare both types of tools, it will be clearly visible by comparing the EL images in Fig. 5a that EL imaging is no suitable method for detecting a failure contact due to soldering issues. In Fig. 5a three unsoldered contacts are hard to discover while using standard parameter due to good conductivity of monocrystalline wafer material.

An explanation on module power degradation in thermal cycling test mentioned in chapter 2 is also shown on single-cell-module level. Using series resistance measurement (the same measurement equipment used for EL) shown in Fig. 5b a clear increase in series resistance is shown due to one failure contact per busbar. This increase of series resistance can cause high interconnection degradation at thermal cycling testing later on shown in Fig. 5b after TC 200. If thermal cycling testing will continue a further increase of contact degradation was proven due to soldering failure and unconnected solder joints compared to the reference.
4. Low wetting rear side as a probable failure mode in production

From the results of the experiments and simulations in the chapters above it could be revealed, that the most detrimental impact on reliability regarding soldering results from the soldering quality of the rear side. The completely disconnected pads lead to strong degradation effects, but of course would be sorted out during production since it is even visible by the naked eye. However a low wetting is not really detectable without a peel test and therefore could appear as a possible failure mode in production if you do not use the right soldering parameters. Furthermore, the impact on module reliability and long term stability of the low wetting behavior for a pad rear side contact is not clear so far.

Therefore it was intentionally evoke the failure mode “low wetting rear side” by adjusting the soldering parameters as it is mentioned in chapter 2 to get modules with this special failure mode manufactured with production equipment. For equipment reasons it was easiest to provoke this failure on the middle busbar on the rear side. To proof the aim of low wetting several peel off tests prior to the test module production were done. As expected due to low wetting the pads of busbar 2 reveal a lower peel force than the pads of outer busbars. As an inset for three representatives peeled off pads the optical appearance is shown. The detailed SEM analysis using a SE (secondary electron) detector is depicted in Fig. 6 a-d. In Fig. 6a a pad detail of 313x magnification shows the typical topography of a soldered rear side contact pad after peel off of the solder ribbon. A similar image in Fig. 6b reveals topography of a rear side contact pad with the low wetting as well after ribbon peel off. At first glance there is no apparent difference to see, but the Fig. 6c (typical pad; 5600x magnify.) and Fig. 6d (low wetting; 3000 magnify.) clearly show the difference, which is after all expected. The areas which have been soldered are highlighted by green circles (not soldered areas with red rectangles) are much more prominent and cover a much higher surface area for the typical soldered rear side pad (Fig. 6c) compared to the much less soldered surface area ratio in the low wetting case (Fig. 6d). Now it is also obviously recognizable in the overview images Fig. 6a+b.
Finally, the SEM analysis reveals, that there actually is a soldered intermetallic connection in the low wetting case too. The main remaining question now is to investigate the influence of a probably weaker solder joint on the reliability of the module. Therefore two 60 cell modules were manufactured containing this specific failure mode, which was proofed as described above by several peel tests before to find the useful stringer recipe. In addition two modules with sufficient solder joint on all pads were used as references in the thermal cycling (TC) test. The TC test was conducted up to 600 cycles. After every 100 cycles a read out was done. Since the main impact of an insufficient solder joint during degradation should be on the series resistance, the Fill Factor ($$FF$$) development is shown in Fig. 7 for both modules with failure mode “low wetting”, named Exp_1 and Exp_2 as well as for both references (Ref_1 and Ref_2).
Fig. 7 Fill Factor development during Thermal Cycling test up to 600 cycles for two experiment modules (red curves) as well as two reference modules (blue curves).

Obviously all modules suffer from a slight degradation in $FF$ over the different TC steps, but there is no significant difference between experiment modules and references.

So finally we can state for long term module stability, means at least for soldered cell rear side to ribbon contacts, it is mandatory to ensure a soldered intermetallic connection between cell contacts and solder ribbon. Long term TC tests revealed that there is no detrimental effect on module long term stability due to the quality of the rear side pad solder joint, but obviously for pads with insufficient soldering.

5. Conclusions

Different possible soldering failure modes on front and backside on module level were investigated. These failure modes were intentionally prepared before module assembly. The data show that different failure modes have different impact on module reliability. The highest influence is obvious from soldering failure modes on the rear side. This was also proven by simulation and production test.

Summarizing all results the author conclude that only one provoked failure mode leads to high impact on reliability. Due to our basic understanding we are able to completely avoid soldering failures on mass production and there for we could investigate these intentionally prepared soldering failures and their impacts on module reliability.

Acknowledgement

The authors like to thank our technical assistants Thomas Linke, Denise Ulm and Antje Standtke as well as our module prototyping and module test center.

References