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Excellent via passivation and high open circuit voltage for large-area n-type MWT-PERT silicon solar cells

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Abstract

In this work, we improved the performance of the MWT-PERT solar cells focusing on increasing their V_{oc} by combining the MWT concept with *n*-PERT technology. The impact of different post-laser treatments on the via surface morphology and the via passivation was investigated. KOH texturing can partially remove the laser damage in the via and reduce the via SRV to 1000 cm/s. With optimized post-laser treatment and via passivation, an average V_{oc} of 685mV was achieved for our large-area *n*-type MWT-PERT cells. Front Ni/Cu plating and rear Ag and Al screen-printing were used for the metallisation, the compatibility of this hybrid metallisation scheme was studied. Using industrial solder-through interconnection technology, the cell was integrated in a laminate reaching a one-cell module efficiency at 20%. The reliability of the one-cell modules was preliminarily investigated in an extended reliability test.

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Keywords: MWT PERT solar cells; via passivation; plating; screen-printing; module reliability

1. Introduction

Crystalline silicon (c-Si) solar cells are currently dominating the photovoltaic market. Different approaches have been investigated to further improve the performance of crystalline silicon solar cells. One approach is to develop back-contact solar cells, such as Metal Wrap Through (MWT) structures [1], which requires only one additional

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processing step (laser via drilling) compared with standard industrial cell fabrication. With both contacts and interconnection at the cell backside, this design does not only reduce shading and absorption losses due to the reduced front metal coverage, which leads to a gain in the short-circuit current density (J_{sc}), but it also improves the aesthetics of the module. The advanced *n*-type PERT cell technology is another innovative approach featuring a dielectric passivation and local contacts on the rear side. Combining the features of the MWT and *n*-type PERT solar cells in an MWT-PERT solar cell architecture will result in a higher current due to minimized shadowing on the front, appealing aesthetics of the cells (no front busbars) and improved open circuit voltage (V_{oc}) due to a better rear passivation. An efficiency of 21% has been reported for large-area *n*-type homogeneous junction MWT PERT solar cells with V_{oc} of 656mV [2]. This champion cell features contacts with screen-printing of Ag and Ag/Al paste and unpassivated vias.

n-type PERT solar cells have demonstrated V_{oc} potential above 690mV in recent publications [3] [4]. In this work, we improved the performance of the MWT solar cells focusing on increasing their V_{oc} by combining the MWT concept with *n*-PERT technology. The impact of different post-laser treatments on the via surface morphology and the via passivation were investigated. KOH texturing can partially remove the laser damage in the via and reduce the via SRV to 1000 cm/s. With optimized post-laser treatment and via passivation, an average V_{oc} of 685mV was achieved for our large-area *n*-type MWT-PERT cells. A hybrid metallisation scheme was implemented in this work. Front Ni/Cu plating and rear Ag and Al screen-printing were used for the metallisation of our MWT-PERT solar cells to reduce the precious Ag consumption and cost. Two main challenges were previously identified for this hybrid metallisation scheme [5]. First, it is difficult to plate continuous fingers near the via printed-through Ag paste, which can prohibit a good contact. Second, for immersion plating tools, the adhesion of the Ag pads after exposure to plating solutions can be severely degraded. Thus, the integration of the hybrid metallisation scheme was investigated in this work, especially on the compatibility of the screen-printing pastes with the plating sequence. Finally, we integrated a number of cells into one-cell laminates using the solder-through interconnection technology [6] and subjected them to an extended reliability test.

2. Approach and experiment plan

2.1. Short-loop test and process optimization

Via passivation and metallisation integration were investigated using short-loop tests. To investigate the via passivation, symmetrical lifetime samples with different via densities were fabricated. After via drilling, a post-laser treatment was applied to remove the laser damage, using KOH saw damage removal (SDR) or KOH texturing. All the samples received then a front surface field diffusion (FSF) and were passivated by a dielectric stack of thermal SiO_2 and PECVD SiN_x on both sides. The process flow and structure of the samples are shown in Fig. 1. (a) and (b). The surface morphology of the via was studied by top-view and cross-sectional SEM, and the lifetime of the samples was measured using BT imaging. The samples were further received a laser doping on the front and screen-printed with Ag via paste on the rear. And the front contact was plated. The via paste printing and firing were well optimized to ensure the solderability of the rear Ag pads after the Cu plating. The adhesion of the Ag pads after soldering was measured by a 45° pull test.

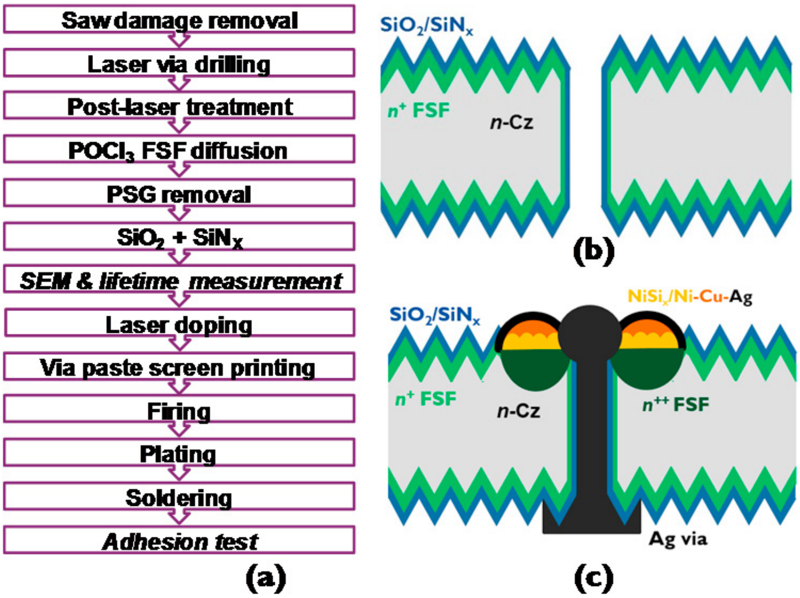


Fig. 1. (a) Processing flow for short loop tests and the structures of the test samples for the study of (b) via passivation and (c) compatible metallisation

2.2. Solar cell process flow and the fabrication of laminated one-cell module

MWT-PERT solar cells were fabricated on 156 mm ×156 mm *n*-type Cz silicon wafers using the process flow shown in Fig. 2(a). The rear metallisation design contains 3 x 9 Ag pads for the n^+ contact and 3 x 9 Ag pads for the p^+ contact to be compatible with the module interconnection. The final cross-section structure is shown in Fig. 2(b). Reference *n*-PERT solar cells were fabricated in the same batch as the MWT-PERT cells. The one-sun *I-V* parameters of the *n*-PERT solar cells were measured in imec using a Wacom *I-V* tester (WXS-200S-20 AAA) with externally calibrated reference cell (ISE CalLab). The one-sun *I-V* parameters of the MWT-PERT solar cells were measured using a flash *IV* tester (Berger Lichttechnik PSS 10), since only this flash *IV* tester has a designated all-back-contact chuck compatible to the rear design of our MWT PERT cells. Solder strips were connected to the rear contact pads of the cell, using industrial solder-through interconnection technology. The soldered MWT-PERT solar cells were laminated into glass-backsheet or glass-glass one-cell modules. A black back-sheet or a black encapsulant was applied correspondingly to improve the aesthetics for BIPV applications.

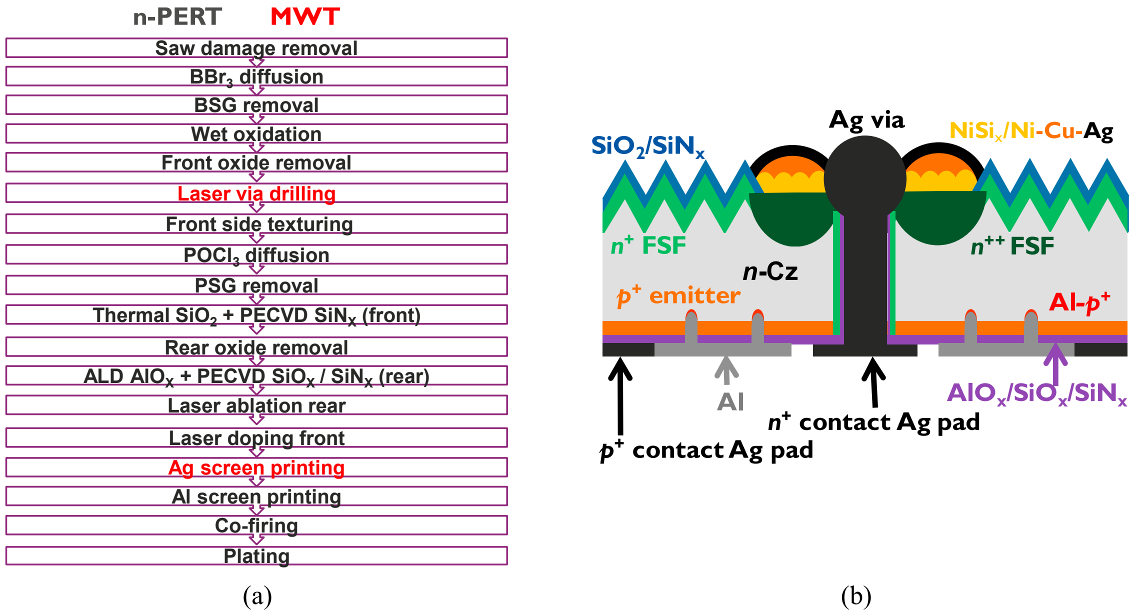
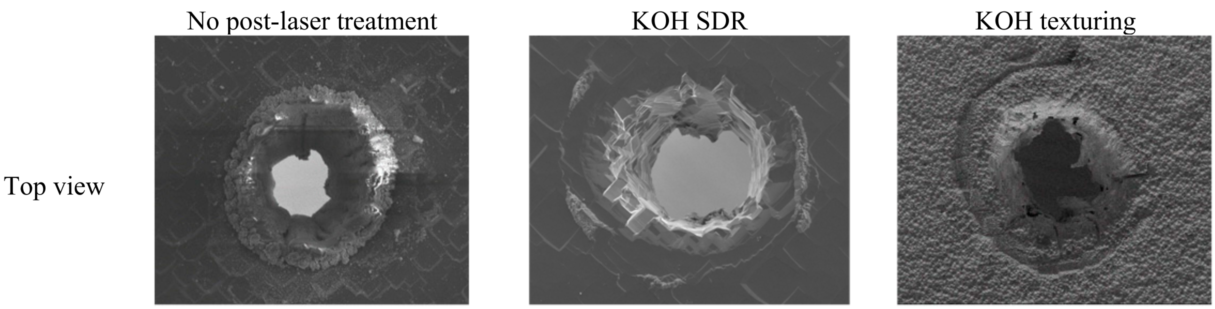


Fig. 2. (a) Process flow and (b) cell structure for our MWT PERT solar cells

3. Experiment result

3.1. Via passivation

To improve the V_{oc} of the MWT-PERT device, it is important that the bulk damage created by the laser drilling is removed, and the via surface is well passivated. After via drilling, a post-laser treatment was applied to remove the laser damage, such as KOH SDR or KOH texturing. The mentioned post-laser treatments are observed to have a significant impact on the surface morphology of the via as shown in Fig. 3. With no post-laser treatment, large areas of molten silicon are observed along the via wall. This molten silicon was completely removed in the KOH SDR solution, and partially removed in the KOH texturing solution. After measuring the lifetime of samples with different via densities, we extracted the surface recombination velocity (SRV) of the vias using Mingirulli's approach [7] as shown in Fig. 4. The via SRV is reduced from 10000 cm/s without any post-laser etching to 1000 cm/s with KOH texturing, or even reduced to about 200 cm/s with KOH SDR. At a via SRV of 1000cm/s, the V_{oc} loss due to the via recombination with our via pattern [8] is expected to be less than 1 mV. Since the KOH texturing process is anyway also required for the front side pyramids formation, it is selected as the post-laser treatment in this work.



(a)

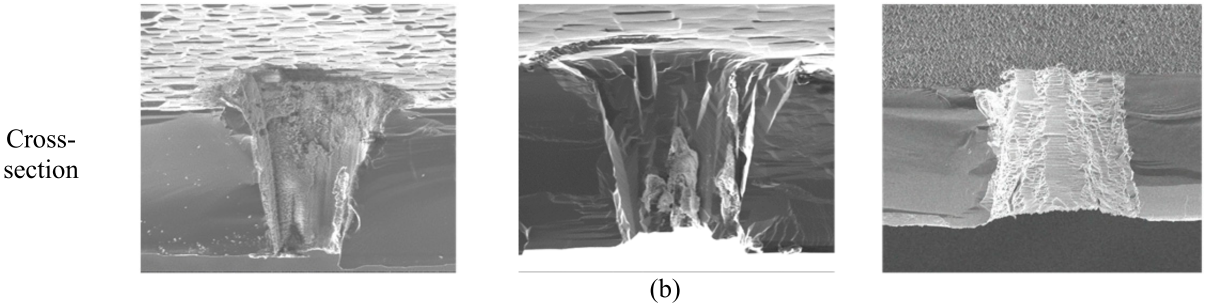


Fig. 3. (a) Top view and (b) cross-sectional SEM of the via surface after different post-laser treatments

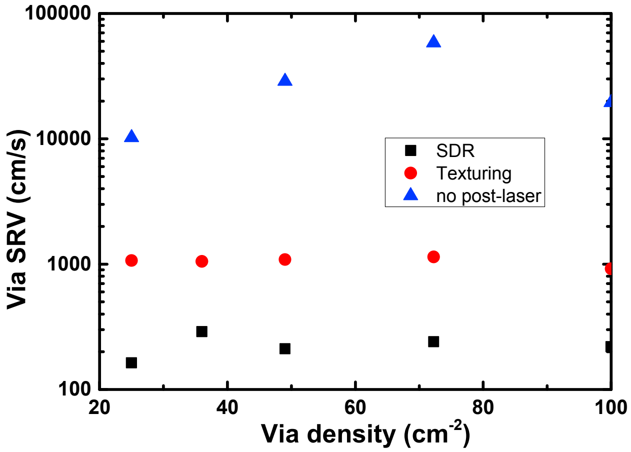
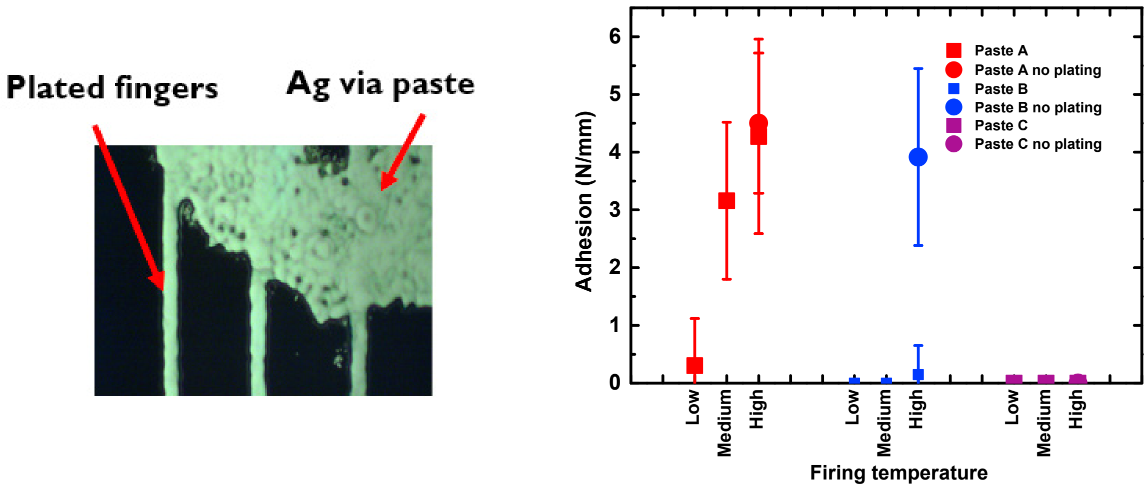


Fig. 4. Calculated via SRV after different post-laser treatments using the Mingirulli's approach [4]. The via SRV is reduced from 10000 cm/s without any post-laser etching to 1000 cm/s with KOH texturing and reduced to 200 cm/s with KOH SDR

3.2. Metallisation integration

A screen-printed via metallisation process which is compatible with Ni/Cu plated front contacts is developed in this work. Plating is advantageous over Ag screen-printing because of lower material cost (no Ag consumption) and higher efficiency potential (narrower contact width). With the combination of plating for n^+ contacts and Al screen-printing for p^+ contacts, a highest V_{oc} of 690mV with an efficiency of 21.7% has been achieved on the *n*-PERT solar cells [4]. This result has demonstrated the performance potential of this hybrid metallisation while minimizing the consumption of expensive Ag. In the development of our MWT-PERT solar cells, additional Ag screen-printing was applied as the via metallisation to contact the front plated finger, and as the Ag pads for module interconnection. As mentioned in the introduction, the compatibility of Ag screen-printing and plating is the main challenge in this metallisation integration.

Lead-free Ag via paste was selected to ensure continuous plating near the via region shown in Fig. 5(a). Pb from the glass frit can dissolve in the Ni solution and adversely affect plating of the first Ni layer [5]. The second challenge is the adhesion of the Ag pads after passing them through the plating solution. We selected three commercially available Ag pastes for the adhesion test. The pastes are all high-temperature (compatible with rear Al paste co-firing) and non-firing-through (not damaging the dielectric layers). The adhesion of Ag pads was tested by a 45° pull test, and the result is shown in Fig. 5 (b). The adhesion of the reference samples without passing through the plating solution was also measured. Only paste A, fired at a medium to high temperature passes the test with adhesion above 1 N/mm after plating. Paste C failed the test even before passing through the plating solution. The adhesion of the Ag pads increases with the increase of the peak firing temperature for paste A. When the adhesion is above 3 N/mm, the failure mechanism is mainly caused by the breakage of the samples.



(a) (b)

Fig. 5. (a) Optical microscope image of continuous front plated finger around Ag via paste (b) Adhesion of different Ag via paste as a function of the peak firing temperature after plating, only paste A passes the test with adhesion above 1 N/mm after plating

3.3. Solar cell result

After optimization of the via passivation and metallisation, MWT PERT solar cells were fabricated on 156 mm ×156 mm *n*-type Cz silicon wafers using the process flow shown in Fig. 2(a). The one-sun *I-V* parameters of the MWT PERT and *n*-PERT solar cells are shown in Table 1. As the pulse width of the flash tester is too short (5ms) to correctly measure cells with high V_{oc}, the fill factor (*FF*) and subsequently the efficiency (η) of the MWT PERT cells were not measured accurately. An average V_{oc} of 685mV has been achieved for our MWT PERT solar cells. Compared with *n*-PERT solar cells, only 2mV of V_{oc} was lost due to via recombination, which agrees with our result in Section 2.1.

Table 1. Average one-sun Voc and Jsc values of n-PERT and n-type MWT-PERT solar cells, the fill factor and subsequently the efficiency of the MWT PERT cells were not measured accurately due to the limitation of the flash tester

	Cell area (cm^2)	V_{oc} (mV)	J_{sc} (mA/cm^2)	*FF* (%)	η (%)
n-PERT	239	687±0.4	39.5±0.1	79.7±0.1	21.7±0.1
MWT PERT	239	685±1.0	40.4±0.1	X	X

3.4. Performance and reliability of laminated one-cell modules

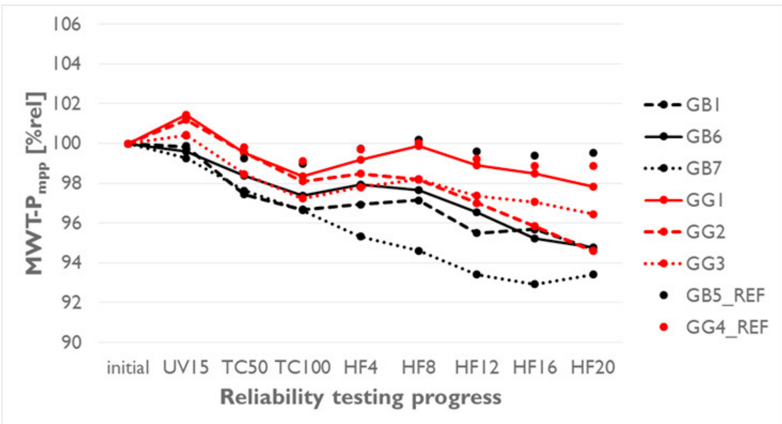
The fabricated MWT PERT cells were further integrated in one-cell modules, using the interconnection technology developed earlier at Photovoltech and Soltech, which is a stringing approach based on soldering through an electrically insulating fabric [6]. Both glass-glass and glass-backsheet laminates were prepared using ARC-coated glass at the front. The one-cell modules were first measured at imec using a Wacom *I-V* tester with externally calibrated reference one-cell module (ISE CalLab). The best one-cell module was also measured in ISE CalLab. A black frame was used in both cases to restrict the current generation to the active area of the cell. The one-sun *I-V* parameters of the best one-cell module (glass back-sheet) measured internally and externally are displayed in Table

2. The V_{oc}, I_{sc} and *FF* and maximum power point, P_{mpp} match well for the two measurements. The discrepancy in the efficiency is mostly due to the difference in the aperture areas of the measurement. Due to the black (encapsulant or backsheet) background next to the cells, the aperture area does not significantly impact the I_{sc} value. The 74.7% *FF* includes the impact of resistive losses both in the cell and in the ribbons that are connected to the cell. We can estimate a slightly higher *FF* (~75%) at the cell level. Using this *FF* of 75%, together with the V_{oc} and J_{sc} in Table 1, we can estimate that our MWT PERT solar cells have an η above 20.5%. Non-optimized rear contact design was identified as the main cause of the lower *FF* (~75%) of the MWT PERT cell compared with the *FF* (79.7%) of the PERT cell, as the rear contact design was fixed in this work to be compatible with the interconnection.

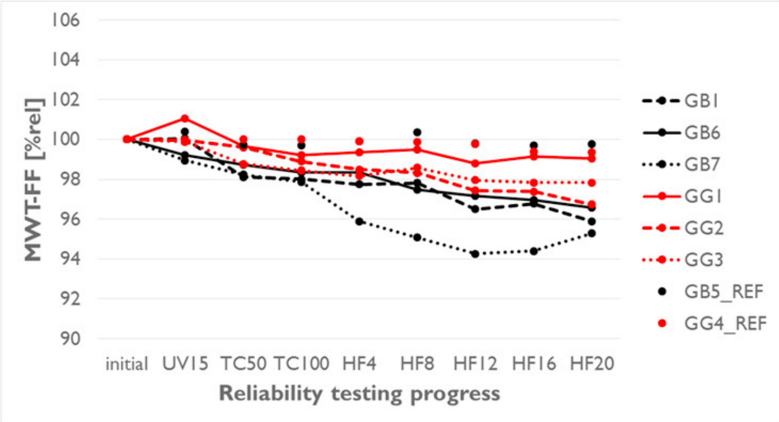
Table 2. One-sun electrical parameters of the best n-type MWT PERT one-cell module measured internally and externally by ISE CalLab. The discrepancy in the efficiency is due to the difference in the aperture areas of the measurement.

	Aperture area (cm^2)	V_{oc} (mV)	I_{sc} (A)	*FF* (%)	η (%)	P_{mpp} (W)
Imec	238.6	686	9.282	74.7	20.0	4.76
ISE CalLab	253.8	685	9.248	74.5	18.6	4.72

The reliability of the interconnection technology has been validated in the past on industrial cells [9]. 6 one-cell modules were subjected to an (extended) reliability test with longer exposure to the humidity-freeze conditions as defined by the relevant IEC standard. For both glass-glass and glass-backsheet buildup, 3 modules were subjected to the testing scheme, and 1 module was kept as reference. The testing sequence consisted of UV pre-conditioning (15 kWh/m^2), followed by thermal cycling (100 cycles between 85 and -40 °C) and humidity freeze testing (20 cycles between 85 and -40 °C, including 85% RH at 85 °C). The cycling is thus twice the amount specified in the certification standard IEC61215. The resulting degradation of these modules is shown in Fig 6. The spread in results is relatively large (93.4-97.8%). From the reference laminates, the error due to measurement deviation is estimated at about 1%. While only 2 of the glass-glass laminates passed our extended test (<5% degradation in maximum power point, P_{mpp}), all of them would probably pass the standard test specified in IEC61215. The degradation is largely attributed to a decrease in *FF*, and can be linked to a gradual increase in series resistance. A minor part, ~1%, is also due to a reduction in I_{sc}, which might be due to a degradation of the ARC of the glass which is optically visible.



(a)



(b)

Fig. 6. Relative performance degradation of (a) P_{mpp} and (b) FF throughout reliability testing of the fabricated laminates

4. Conclusions

In conclusion, we report our progress of the large-area *n*-type MWT PERT solar cells, focusing on increasing their V_{oc} by better via passivation, and reduction of Ag consumption by using plating and screen-printing of Ag via and Al rear. The impact of different post-laser treatments on the via surface morphology and via passivation was investigated. KOH texturing can partially remove the laser damage in the via and reduce the via SRV to 1000 cm/s. With optimized via passivation, an average V_{oc} of 685mV is achieved for the MWT PERT cells. The compatibility of the hybrid metallisation scheme has also been integrated. Lead-free Ag via paste was selected to ensure continuous plating near the via region. Only one paste passes the test with adhesion above 1 N/mm after plating. The adhesion of the Ag pads increases with the increase of the peak firing temperature. Using industrial solder-through interconnection technology, the cell was laminated reaching a one-cell module efficiency at 20%. 2 of the glass-glass laminates passed our extended humidity freeze test (double amount of cycles as specified in the IEC61215). The degradation of other one-cell modules is also less than 7%. All of them would probably pass the standard test specified in IEC61215.

Acknowledgements

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