THE EFFECTS OF ACCELERATED AGING TESTS ON METAMORPHIC III-V CONCENTRATOR SOLAR CELLS MOUNTED ON SUBSTRATES

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ABSTRACT: Various stress tests have been applied to metamorphic III-V concentrator solar cells mounted on substrates. The duration of the tests was up to 3000 hours in order to provoke accelerated aging and to identify whether any degradation occurs. Effects introduced due to the applied stress were expected to be seen in light IV curve measurements. Therefore, we investigated the stressed samples by light IV measurements under high intensity levels, optical inspection by a light microscope and an elemental analysis by SEM-EDX. Reference samples were used to evaluate the characterization methods for IV measurements and to confirm the test results. Neither total failures nor critical degradation in the IV characteristics were observed for more than 70 test samples, which underwent stress procedures including damp heat, thermal cycling, humidity freeze and high temperature tests.
Keywords: Multi-junction Solar Cells, Accelerated Aging, Qualification and Testing, Characterization

1 INTRODUCTION

The highest solar cell efficiencies have been reached with monolithic III-V triple-junction solar cells. Thus, these devices are commercially attractive for space applications as well as in terrestrial concentrator photovoltaic (CPV) systems [1,2]. Commercial concentrator cells have been available for years from several cell manufacturers, e.g. [3,4,5,6]. A new IEC standard to qualify solar cells as well as receiver for CPV applications is under discussion [7,8]. Therefore, it is necessary to define new test sequences in contrast to IEC 62108 in which only one test at the receiver level is mandatory [9]. This standard was successfully established in 2007 to prove and qualify new designs for CPV modules and assemblies. However, new tests are required that are adapted to the specific demands of the cells and receivers. Several stress tests have already been suggested to qualify concentrator cells on bare cell level as well as for mounted cells [7,10,11,12].

A promising approach to further increase solar cell efficiencies is the concept of metamorphic growth. The benefits of metamorphic III-V multi-junction solar cells has already been discussed elsewhere e.g. [13,14,15,16]. The basic idea of this concept is to integrate special buffer layers which allow modifying the lattice constant. Thus one can design the band gaps of the monolithic solar cell structure more freely, which is the key to the optimization of a multi-junction cell. In this paper, we examine metamorphic triple-junction solar cells of $Ga_{0.35}In_{0.65}P/Ga_{0.83}In_{0.17}As/Ge$. The buffer layers show severe misfit dislocations and other defects to overcome the lattice mismatch of 1.1 % [15]. Under thermal stress, for example, these defects might penetrate into the electrically active cell layers above. If this happens, the misfit dislocations will probably entail a degradation of the solar cell and thus a reduction in the electrical performance. First promising results regarding the stability of metamorphic concentrator solar cells have already been published, see [10,11]. However, metamorphic triple-junction solar cells which were developed at Fraunhofer ISE showed significant degradation after thermal cycling [17]. Only a few samples were here tested so far. So the aim of this work is to study the stability of this type of metamorphic cell under different stress conditions on the basis of a high number of samples.

2 EXPERIMENTAL

2.1 Industrial concentrator cell and receiver

For this study, multiple metamorphic wafers were grown by MOVPE at Fraunhofer ISE. The epitaxial wafers were further processed to solar cells at AZUR SPACE solar power, including front and back surface metallization, deposition of antireflection coating (ARC) and mesa etching. The active cell area is 0.0425 cm². For handling purposes the solar cells were mounted on copper substrates. A mounted metamorphic concentrator solar cell is shown in Fig. 1. This type of concentrator cell can be used in Fresnel lens-based CPV modules like the FLATCON® concept [18,19].

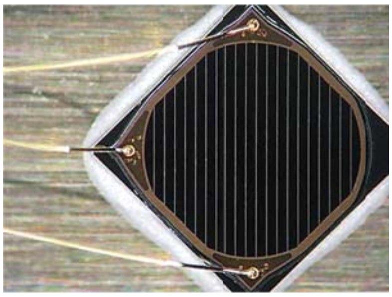

Figure 1: Light microscope image of a metamorphic $Ga_{0.35}In_{0.65}P/Ga_{0.83}In_{0.17}As/Ge$ triple-junction concentrator solar cell which is mounted on a substrate.

The manufacturing of the cell assemblies (receiver) was carried out in a fully automated production process at Soitec Solar, Freiburg. More than 2000 test samples were processed in an industrial manner ensuring a minimization of process parameter variations. For characterization and assembly purposes, a bypass diode is also attached to the substrate. This corresponds to a standard CPV receiver design for FLATCON® type modules [20], which is shown in Fig. 2. In our investigations neither the cells nor the substrates were encapsulated.

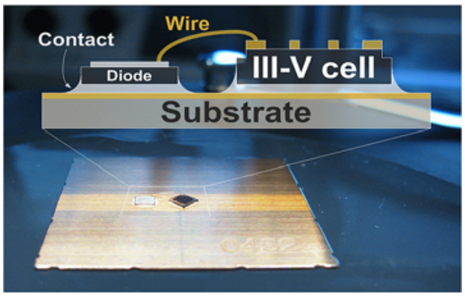

Figure 2: Photograph and schematic of the CPV receiver design (test samples).

The back surfaces of bypass diode and solar cell are attached to the substrate by an electrically and thermally conductive adhesive. The connection between the front metallization of cells and diodes is accomplished by thin gold wire bonds. All receivers (test samples) were processed in the same production batch (AV100).

2.2 Stress tests and conditions

Four accelerated aging tests (below also referred to as stress tests) were carried out to ascertain which defects and degradation may occur under different stress conditions. Table 1 lists all stress tests, the overall duration of each test and the last date of characterization. In addition, the references for the chosen test conditions are given. The testing will continue until a test duration of at least 6000 h is reached.

Table 1: List of stress tests, overall duration of each test, the date of the latest characterization and the reference for the chosen test conditions.

Stress test		**Duration** [h]	**Date** [MM/YY]	**Ref.**
Damp heat	(DH)	3000	08/11	[9]
Thermal cycling	(TC)	2500	08/11	[21]
Humidity freeze	(HF)	1600	07/11	[9]
High temperature	(HT)	1500	08/11	-

Neither the cell nor the chip surface, which also includes the substrate, is covered by any encapsulation or protective coating. The performance may especially be reduced by a degradation of the cell surface, which can be the ARC or the cell perimeter, caused by, for example, oxidation. In order to analyze the effects of high temperature (150 °C) as well as damp heat (85 °C/85 % RH) on metamorphic concentrator solar cells, two tests were defined. Due to the defects in the crystal structure within the metamorphic buffer layers thermal stress might be a critical issue for the long-term stability of metamorphic solar cells. A simple thermal cycling test (-30 °C to 130 °C, Fig. 3) has been applied to investigate if defects might move into active cell layers. A humidity freeze test (-40 °C to 85 °C/85 % RH, see Fig. 4) was selected to prove the stability of the test samples under combined stress conditions.

2.3 Temperature cycle

The target for the thermal cycling test was a maximum duration of 1 h per cycle [21]. This value has not been achieved due to the limited temperature rate of the climate chamber. In the experiment performed here, temperature limits of -30 °C and 130 °C were chosen and a cycle duration of 2 h was reached. A lower temperature limit of -40 °C will double the cycle duration. Compared to IEC 62108, the maximum temperature is higher, in order to increase the stress on the sample. The conditions in the test chamber were always monitored by two temperature sensors. Fig. 3 illustrates the measured temperature profile of the test chamber as well as of a test sample compared to the targeted temperature cycle.

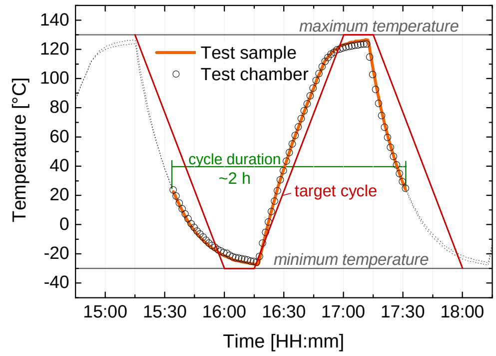

Figure 3: Temperature cycle in a climate chamber at Fraunhofer ISE. Actual temperatures of the chamber and a sample were monitored with two temperature sensors. Additionally, the target cycle is shown.

In Fig. 3 the duration of one cycle is shown. The bold line and the circles represent the temperatures measured at the sample and in the chamber, respectively. A good agreement between both measured temperature profiles is found. A maximum temperature difference between test chamber and sample of only 5 K was detected. However, in order to achieve the target temperatures, dwell times (15 min) as well as heating and cooling rates, the settings for the thermal cycling test were modified after 2500 h.

2.4 Humidity freeze cycle

The settings for the humidity freeze test were based on the equivalent test for CPV modules in IEC 62108 to evaluate the applicability on the cell/receiver level. In order to verify the conditions in the corresponding climate chamber, the temperature (line) and the relative humidity (squares) were monitored by internal sensors for 24 h. The sequence of the humidity freeze test is shown in Fig. 4. The temperature limits as well as the relative humidity (RH) of 85 % at 85 °C were reached. Step functions were used to heat and cool with maximum power.

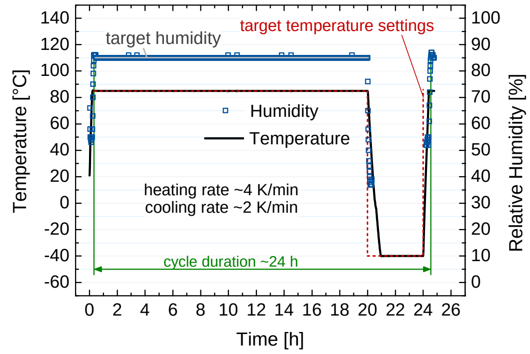

Figure 4: Humidity freeze cycle in a climate chamber at Fraunhofer ISE. Temperature and relative humidity were logged by internal sensors. The programmed test cycle settings are also displayed.

As the cooling rate (2 K/min) was lower than the heating rate (4 K/min), the settings were adapted after 1600 h. Also, the climate chamber was further on remotely controlled by software in order to achieve equal heating and cooling rates and a cycle duration of exactly 24 h.

3 CELL CHARACTERIZATION METHODS

3.1 Laboratory flash setup

A laboratory flash setup was used for the IV measurements of the metamorphic solar cells. This setup has a short flash interval of less than 30 s, meaning the charging time between two flashes. Thus, a fast characterization of a large number of solar cells is feasible. For this work, the test samples were measured at a light intensity level of 35 W/cm². In order to reach this intensity value, the flash bulb must be positioned directly over the receiver at a distance of less than 5 cm. Hence, the height of the bulb must be readjusted for each measurement due to the manual contacting of the solar cell to the measuring equipment. The bracket holding the flash head was adjusted by a test measurement before characterization. Therefore, a test sample was introduced as reference sample. The sample AV100-0366ref was not exposed to any accelerated aging and, in addition, was used for the evaluation of the measurement accuracy for this characterization method. Based on the measured short circuit current (I_{SC}) of the reference sample, the measurements of the aged samples were performed at an intensity level of about 35 W/cm². Fig. 5 shows the minimum, maximum and mean measurement values of I_{SC} and V_{OC} for the reference sample. At each characterization step of a test batch the reference sample was measured several times, except in step 3. A test batch contains all test samples which went through one of the stress tests.

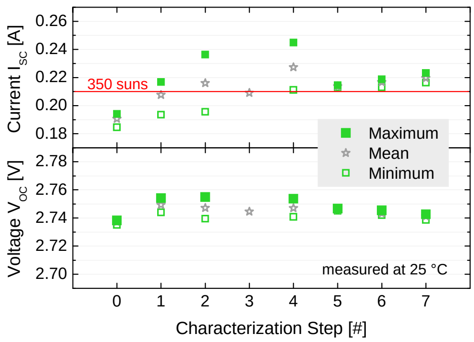

Figure 5: Minimum, maximum and mean values of short circuit current and open circuit voltage for the reference sample AV100-0366ref at each characterization step of a test batch.

The evaluation of the results from the reference sample indicates that this characterization method requires further development. The mean values of I_{SC} show that the target value of 0.214 A, corresponding to 35 W/cm², for the reference sample was not met for all steps. This is especially true for steps 1 and 4. The readjustment of the flash head has led to a higher uncertainty than expected. Due to the variation in the measured current of the reference sample and thus in flash intensity for further evaluation of the data of the aged cells, the mean measurement values of the test batches will be normalized to the mean values of the reference sample.

3.2 Development of a suitable characterization sequence for reliability testing

A new tool for automated measurements of concentrator solar cells under high light intensities was assessed at Fraunhofer ISE. The flash simulator is designed to classify CPV receivers with a passive heat sink (see Fig. 2) by light and dark IV measurements in a fully automatic and highly accurate process. Fig. 6 shows a photograph of the fully automated flash simulator (in the following: prober).

Figure 6: Photograph of the fully automated flash simulator for light and dark IV characterization of CPV receivers at Fraunhofer ISE.

A magazine with 20 carriers (or 200 receivers) can be characterized automatically. The carriers are loaded to the measuring chamber. All cells in a carrier are simultaneously connected electrically before the dark and then the light IV characteristic of each cell are measured. The measurement accuracy of the prober was evaluated within the scope of this work. The repeatability of the flash intensity was examined by a reference carrier from batch AV100. After 10 test-runs over a period of several months, a maximum deviation of the mean I_{SC} of ±1.8 % (461±8 mA) was determined on reference samples AV100-2062ref. This means that, the prober allows an automated and fast characterization of CPV receivers in large quantities with a sufficient repeatability for reliability testing.

4 DISCUSSION

4.1 Thermal cycling and humidity testing

The test samples for damp heat, thermal cycling and humidity freeze tests were characterized by light IV measurements using a laboratory flash setup. First all samples were characterized together before the tests and then after increasing stress durations for each test batch separately. Fig. 7 to Fig. 9 show the normalized mean values of I_{SC}, fill factor (FF) and V_{OC} for the batches as a function of time for each test. The normalization of the mean values was necessary to correct the variations of the light intensity between the characterization steps (compare section 3.1 and Fig. 5). Therefore, the mean value I_{SC}, FF and V_{OC} of each test batch was divided by the corresponding mean value of the reference sample AV100-366ref. The reference sample was not exposed to any accelerated aging and was measured several times throughout the characterization campaign. These ratios for each characterization step were normalized to the ratio at initial characterization (stress duration 0 h).

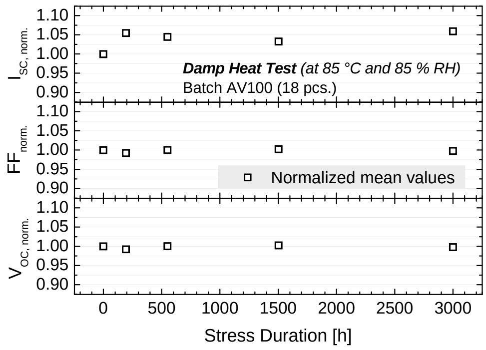

Figure 7: Normalized mean values of short circuit current, fill factor and open circuit voltage for the test batch (18 samples), which are aged under damp heat condition.

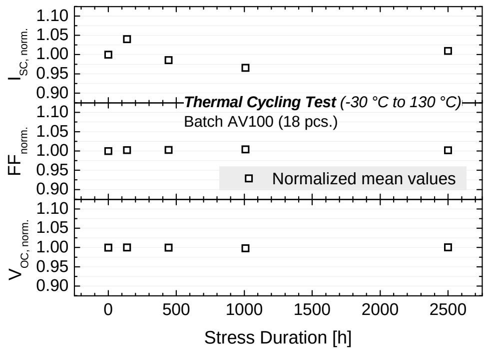

Figure 8: Normalized mean values of short circuit current, fill factor and open circuit voltage for the test batch (18 samples), which are aged under thermal cycling.

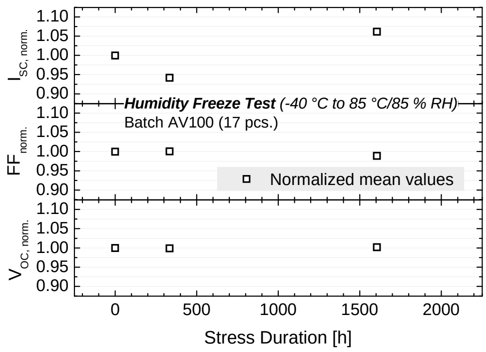

Figure 9: Normalized mean values of short circuit current, fill factor and open circuit voltage for the test batch (17 samples), which are aged under humidity freeze condition.

The metamorphic concentrator cells show no change in FF and V_{OC} due to exposure to thermal cycling and humidity within the measurement accuracy. The normalized mean values of I_{SC} show a higher variation compared to FF and V_{OC}, but also no trend of degradation. Most notably, no critical change in the performance of metamorphic cells due to thermal cycling, as described in [17], was measurable after 2500 h (or 1250 cycles). However, the reduction in FF shows a slight trend to decreasing values after 1600 h under humidity freeze conditions. However, this trend must be verified by further testing. Thus, so far, neither a degradation of the material quality as well as nor a total failure were observed for the non-encapsulated test samples. The results also demonstrate that, so far, the metamorphic buffer structure between the middle and the bottom cell does not lead to instability under temperature changes.

4.2 High temperature storage

A test batch of 20 test samples was kept at 150 °C and was characterized using the prober described in section 3.2 after 500 h and 1500 h. This facility enables degradation to be scrutinized by light IV measurements and the use of a reference sample AV100-0432ref. This sample was not exposed to any accelerated aging and measured in addition to the test batch. Fig. 11 shows the measured values of P_{MPP}, I_{SC} and $V_{OC.}$ The initial values (0 h) for all test samples as well as for the reference sample were here set to one in order to see the relative changes in the parameters. The results for the reference sample indicate a reproducible flash intensity due to constant values of $I_{SC,}$ and a small temperature rise for the third measurement at 1500 h due to a small decrease in measured V_{OC}.

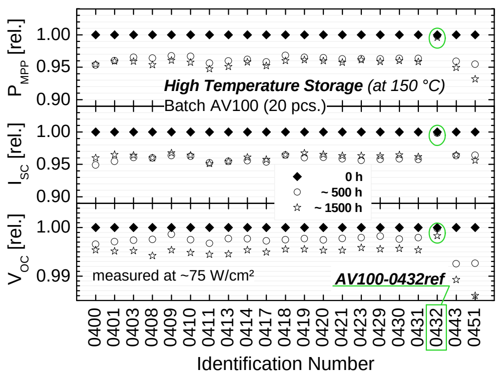

Figure 10: Change of maximum power, short circuit current and open circuit voltage for a batch of test samples due to high temperature storage at 150 °C. Additionally, a non-aged reference sample was measured.

The test samples show a decrease of about 4 % in P_{MPP} and I_{SC} already after 500 h at 150 °C. After 1500 h, no further deterioration was measured compared to the reference sample. A minor additional drop in V_{OC} is observable after 1500 h which, however, can partly be explained by temperature effects (compare V_{OC} of reference sample after 1500 h). Only two samples showed a drop in V_{OC} of more than 1 %. Most likely the power degradation observed here is caused by a change (e.g. oxidation) to the optical surface of the cells, as the main driver for the drop in P_{MPP} is the I_{SC} of the cells (compare Fig. 10).

4.3 Investigation of optically visible degradation

After the test durations indicated in Table 1, a visual inspection of the solar cell surfaces was performed using a light microscope. All stress conditions except thermal cycling led to a change in the color of the metallization, the gold wires and the adhesive. This is most likely caused by oxidation due to contact with hot air or high humidity. The visible changes (highlighted by arrows) for four representative test samples of each test and batch are displayed in Fig. 11. Both a reddish discoloration of the metallization for high temperature conditions and of the adhesive for humidity freeze conditions is apparent after accelerated aging. The contact with humidity also caused white stains on the surface of the germanium substrates, which can be seen in the photographs marked with DH and HF. Here, white spots cover the chip edges around the bus bar.

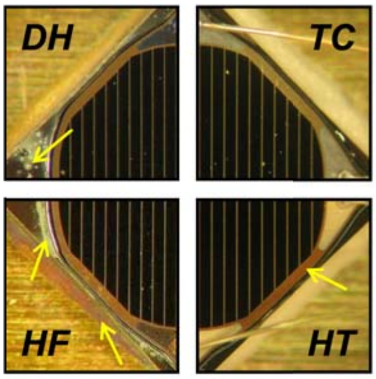

Figure 11: Photographs of four test samples which were exposed to different stress conditions. A color change of the metals and white spots on the germanium substrate are visible (highlighted by arrows).

The test samples are not encapsulated by any protection coating. Further investigations and testing is required to precisely determine the conditions that promote the formation of the white spots and also to clarify whether these spots tend to propagate on the cell surface.

4.4 Analyzing the germanium surface by SEM-EDX

In order to determine the chemical composition of the white stains on the germanium substrate, two test samples were analyzed by SEM-EDX at Fraunhofer ISE. The test samples are shown in Fig. 11 (left photographs) and were stressed by damp heat for 3000 h and by humidity freeze for 1600 h, respectively. First, the germanium surface was inspected by SEM. A change of the surface morphology was identified inside the white areas on the germanium substrates. Then a section (see inlay picture in Fig. 12) was analyzed by EDX to determine the atomic structure of the grains. Fig. 12 shows the EDX spectrum for the marked cycle in the inlaid picture.

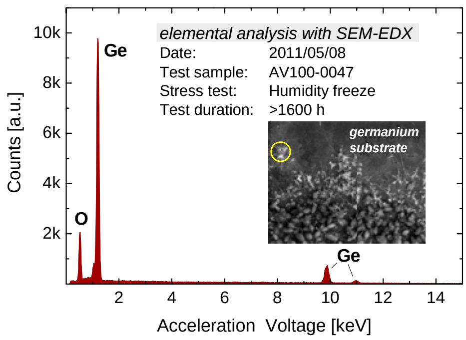

Figure 12: EDX spectrum of a microscopic grain on the germanium substrate of a test sample which was stressed over 1600 h under humidity freeze conditions.

Two elements were detected in terms of this elemental analysis: germanium (Ge) and oxygen (O). As a consequence, a formation of germanium oxide caused by testing under humidity conditions was concluded. For comparison, areas without visible degradation were analyzed. No oxygen was detected on the blank germanium surface. Further detailed experiments are necessary to examine which conditions abet the formation of germanium oxide.

5 CONCLUSIONS AND SUMMARY

More than 70 metamorphic concentrator cells were stressed by damp heat (3000 h), thermal cycling (2500 h), humidity freeze (1600 h) and high temperature (1500 h). A laboratory flash setup was used for the measurement of the light IV characteristics under high intensity. However, it has been shown that the uncertainty of the characterization method is in the maximum range of 15 % for I_{SC}. Thus, only very serious degradation of the cells can be reliably tested using electrical performance parameters. On the other hand, a fully automated flash simulator was introduced that increased the measuring accuracy. In addition, this characterization tool enables the characterization of larger quantities of samples.

The electrical characterization showed neither total failures nor critical degradation in the IV characteristics (within the measurement accuracy) of the test samples after exposure to different stress conditions. This means that the buffer structure of a metamorphic triple-junction concentrator cell is designed to withstand temperature changes as performed by the thermal cycling test (-30 °C to 130 °C) and humidity freeze test (-40 °C to 85 °C). The test results for V_{OC} and FF confirm this conclusion as no changes in the electrical parameters were determined within the measurement accuracy. However, degradation of about 4 % with respect to the maximum power was observed already after 500 h at 150 °C. After 1500 h no further power degradation was detected except on a single sample. Additionally, for damp heat and humidity freeze conditions, visible degradation was identified due to white stains on the germanium substrate. By SEM-EDX, these formations were identified as germanium oxide. Apparently oxidation was caused by exposure to high temperature and humid environment. This effect is not particular to the metamorphic growth concept as also other III-V concentrator cells are also grown on germanium substrates. It should be noted that the correlation between the test results and real operating conditions needs to be studied in future work.

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