

MEASURING THERMOMECHANICAL DISPLACEMENTS OF SOLAR CELLS IN LAMINATES USING DIGITAL IMAGE CORRELATION

Ulrich Eitner¹, Marc Köntges¹ and Rolf Brendel^{1,2}

¹Institut für Solarenergieforschung Hameln (ISFH), Am Ohrberg 1, D-31860 Emmerthal, Germany

²Institut für Festkörperphysik, Leibniz Universität Hannover, Appelstraße 2, D-30167 Hannover, Germany

ABSTRACT

Solar modules are commercially fabricated for more than 30 years but there is little knowledge about its thermomechanical properties. Solid materials shrink or expand when subjected to temperature changes. The coefficients of thermal expansion (CTE) for silicon and glass are small compared to the CTE of the polymer sheets. This CTE-mismatch leads to mechanical stress and strain which can be critical for the solar cells, the interconnects and the polymers. We demonstrate that the digital image correlation technique (DIC) is capable of measuring displacements in modules that are within a climate chamber by an optical measurement through a transparent back sheet and one layer of encapsulation material. As a first demonstration the change of the gaps between adjacent cells is determined at various temperatures for three test laminates with three different interconnection techniques. We find the gap between two solar cells to deform about $0.4 - 0.6 \mu\text{m}/^\circ\text{C}$ in the temperature range of 0°C to 80°C and slightly less in the temperature region below 0°C . The results are verified by a simplified calculation of the gap deformation.

INTRODUCTION

Materials with different thermomechanical properties elongate or contract to different extent when subjected to temperature changes. If the material is not constrained and may freely expand then no stresses are created. In layered structures with perfect bonding between the materials, such as photovoltaic modules, the expansion is constrained by the adjoining layers which results in thermomechanical stresses. Besides the coefficients of thermal expansion, which describe the unconstrained thermal strain per $^\circ\text{C}$, the stiffness of the materials affect the build up of local stress and strain. This problem is referred to as the CTE-mismatch and is one possible reason for module failures, such as delamination, failure of interconnects and solders or microcracks in solar cells. For a detailed analysis of these thermomechanical properties of PV laminates a measurement technique is required.

The digital image correlation technique allows contactless, non-destructive and full-field displacement and strain measurements of objects with a speckled surface. For PV laminate samples with a transparent back sheet we found the digital image correlation technique with a stereo camera system (3D-DIC or DISC) to be a well suited method as the deformation of the embedded solar cells becomes accessible by viewing through the transparent back sheet and one layer of EVA. We reported the accuracy of such PV laminate measurements with

DIC to be below $1 \mu\text{m}$ in displacement. Furthermore, the method is not restricted to special sizes of measurement regions as it only records relative extents and can thus be applied to the small regions such as the gap between to adjacent cells as well as to large regions such as the whole module. The absolute displacement and strain values are determined with the help of a calibration procedure before or after the measurement. The preparation of the test samples is simple as only one additional step, i.e. applying a speckle pattern to the rear surface of the solar cells, is necessary in the usual process of module manufacturing.

DIGITAL IMAGE CORRELATION TECHNIQUE

The method of digital image correlation technique is a common measurement method for mechanical engineers in different application fields for example micro-electronic packaging [1,2,3], polymer engineering [4] or biomechanics [5]. Its use has increased over the last years and by now various systems and software are commercially available. Here we use a system by isi-sys consisting of two 5 Megapixel CCD cameras and the vic3D-software by Correlated Solutions.

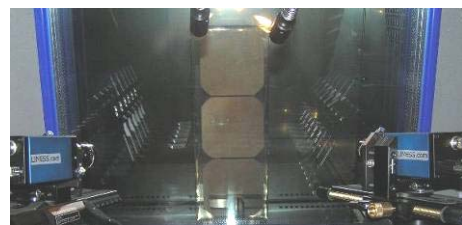
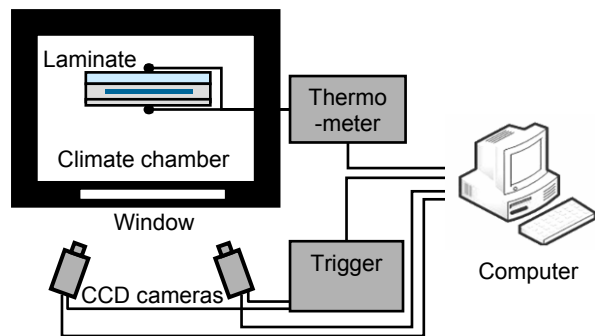


Fig. 1. Digital image correlation system with a stereo camera system. The laminate is measured through the window of a climate chamber.

Two CCD cameras mounted on a rigid rig take simultaneously pictures of the speckled surface of the inspected object. Both images are then correlated by a computer algorithm that calculates a 3-dimensional representation of the surface. Displacements are measured by comparing the 3-dimensional geometric representation of a reference state to a loaded state of the object. In order to correlate the stereo images the correlation algorithm needs information about the orientation and position parameters of the cameras as well as the intrinsic parameters of each camera. These parameters are determined by a calibration, which is performed by recording a calibration target in various orientations before the correlation.

For a more detailed description of the method we refer the reader to publications of Orteu [6] and Sutton [7].

SAMPLE PREPARATION

The application of the DIC method requires a random speckle pattern on the surface of the measured object. As we are interested in the deformation of the solar cells in the laminate, we apply a speckle pattern to the rear side of the cells before lamination. We use temperature resistant spray paint to cover the rear surface completely white. When dry a black pattern is sprayed on the white background. We found the thickness of the paint layer to be between 20 and 40 μm . We start the lamination when the paint is completely dry to avoid the formation of bubbles and the smearing of the paint. Two test laminates are prepared. For laminate A we place three solar cells ($125 \times 125 \text{ mm}^2$) with the applied speckle pattern between two transparent sheets of uncured ethylene vinyl acetate (EVA, etimex vistasolar 486.00) that are laid on top of a 4 mm thick glass plate. The cells are not interconnected. The glass plate, and thus the laminate, is 40 cm by 15 cm in size. We cover the rear side of the assembly with a transparent back sheet (isovoltalcosolar T 2754) which is a composite material with a thickness of 100 μm consisting of polyethylene terephthalate (PET) and an ethylene tetrafluoroethylene (ETFE) core. This assembly is laminated at 150°C for 13 min. The EVA cures by crosslinking its molecular chains and adheres to the cells, the glass and the back sheet. After lamination the sample has a thickness of 5.0 to 5.2 mm. It is important to assure that the surface of the back sheet is completely flat and parallel to the speckled rear side of the cells after lamination. The presence of a surface structure of the back sheet for example in form of little lenses as shown would influence the optical path from the speckled and buried surface to the camera and thus prohibit an accurate measurement.

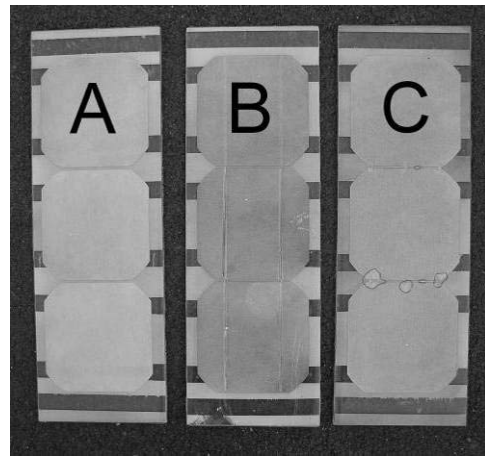


Fig.2: Three laminates with speckle pattern on the back side of the solar cells and on the inner surface of the glass. Laminate A without interconnection, laminate B with standard interconnection and laminate C with H-shaped back contact interconnector.

The second PV test laminate (laminate B) contains three standard interconnected solar cells. Before coating the rear sides of the cells two copper ribbons (2 mm wide and 130 μm thick) are soldered to the front and rear side of each cell. The third test laminate contains 3 back contact solar cells. Each of the two interconnectors is laser soldered to two adjacent cells connecting at six solder points. The connectors are H-shaped, so that two solder points are connected on a direct path. The rest of the preparation procedure for laminates B and C is the exactly the same.

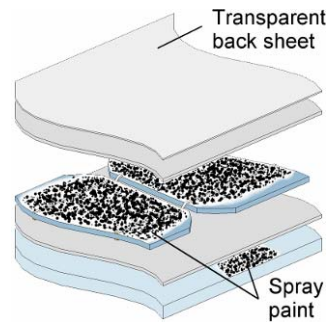


Fig 3: Scheme of laminate prepared for DIC measurement of gap deformation.

MEASUREMENT

Two temperature sensors are attached to the sample before placing it in the climate chamber, one on the front side to the glass and one at the same point on the rear side of the laminate to the back sheet. We position the camera system in front of the window of the chamber facing the rear side of the laminate, where the speckle pattern is visible through the back sheet and one layer of the encapsulating EVA. We then set up the optimal illumination of the object by arranging a cold-light source in front of the window. Once the cameras are focused to

the object, the calibration target is photographed through the window in various orientations inside the chamber. Afterwards a reference state at room temperature is recorded by the stereo system viewing through the window. We then begin the experiment by heating the chamber to 85°C taking a picture approximately every 10°C. The exact temperature of the sample is read from the attached thermocouples. The sample is then cooled down to -40°C.

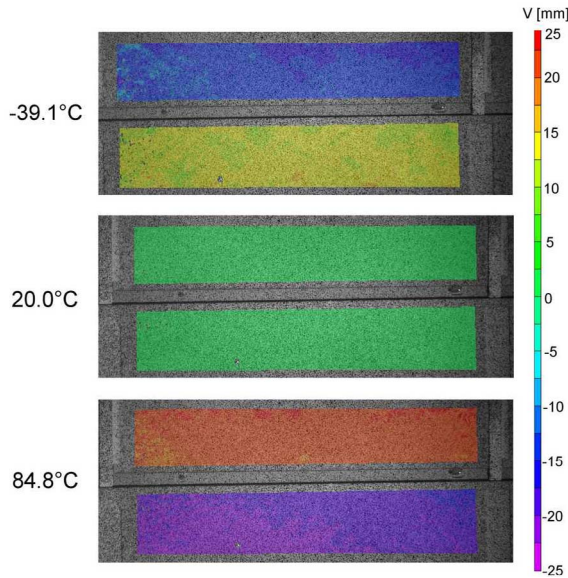


Figure 4: Inspected AOI's of laminate B. Colours indicate the displacement at 3 different temperatures.

RESULTS

After the measurement we define an area of interest (AOI) on the images of the inspected surface, where the strain and the displacement with respect to the reference state are computed. We choose the cell regions that are directly next to the gap between two neighbouring cells as AOI's. The rigid body displacement and rotation is removed by an average transformation. Figure 4 shows the AOI's and the displacement values in vertical direction V for 3 different temperatures. Compared to room temperature, the regions near the cell gap move 20 μm in vertical direction at 84.8°C. We find the gap to widen when rising the temperature and the gap to shrink when lowering the temperature. The opening and closing of the gap between two cells is computed from the displacement data of both AOI's by first averaging the vertical displacement over each AOI and second subtracting these average values. This difference is referred to as the change of cell gap width. It is shown in figure 5 for different temperatures. The graph has a linear behaviour for temperatures above 0°C and a less steep slope below 0°C.

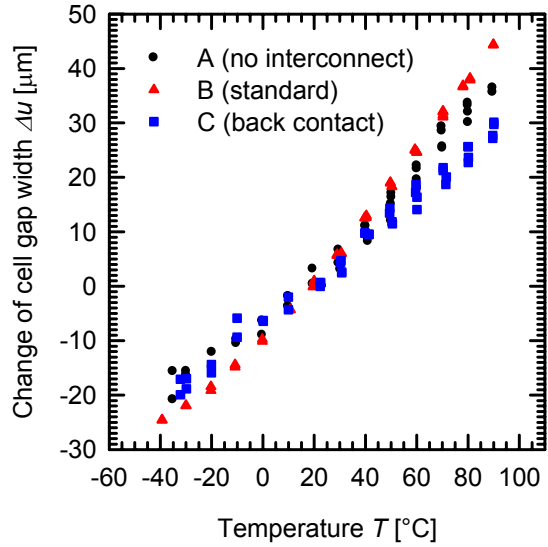


Figure 5: Change of cell gap width at different temperatures (reference state at 20°C) for laminates A, B and C.

DISCUSSION

A detailed study on the accuracy of comparable measurements of photovoltaic laminates with DIC is given in [8] where the different contributions to systematic errors such as refraction of the back sheet, the resolution of the measurement system and the impact of the thick window of the climate chamber are discussed, proving an accuracy of 1 μm in displacement.

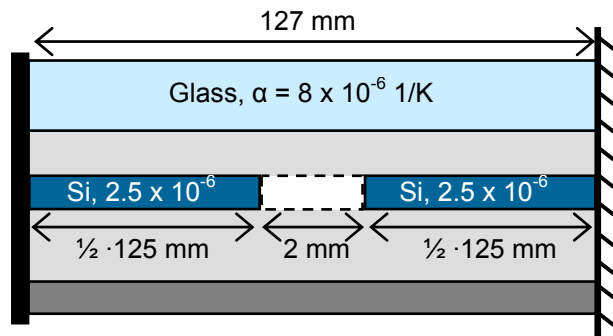


Figure 6: Scheme for simplified theoretical plausibility check of laminate measurements

In order to investigate the plausibility of the measured deformation values, the following basic assumptions are made. The stiffness of the encapsulating polymer EVA is 3 orders lower than the stiffness of the other materials glass and silicon. If we neglect the local influence of the EVA to local strains of the adjoining materials, the deformation of the cell gap is only dependent on the thermal deformation of the glass and the silicon. Regarding the region of the laminate between the midpoints of two solar cells the change of cell gap is the difference between the expansion of the glass and the expansion of the silicon in that region. With a cell width of 125 mm and a cell gap width of 2 mm at the reference state the

region has a length of 127 mm. Under the assumptions that the polymers do not contribute to thermal deformation above 0°C and that the relative thermomechanical deformation of solar cells relative to the glass almost zero, the gap deformation is the difference of glass and cell deformation,

$$\frac{\Delta l_{\text{Glass}}}{\Delta T} = \frac{\Delta l_{\text{Si}}}{\Delta T} + \frac{\Delta l_{\text{Gap}}}{\Delta T} \quad \text{with} \quad \frac{\Delta l}{\Delta T} = \alpha \cdot l.$$

α is the coefficient of thermal expansion and l is the length of the undeformed material. This simplified model is shown in figure 6. Inserting the values from configuration shown figure 6 in the equations above leads to a glass deformation of 1.02 $\mu\text{m}/^\circ\text{C}$ while the half parts of the silicon solar cells expand only 0.31 $\mu\text{m}/^\circ\text{C}$. The difference 0.71 $\mu\text{m}/^\circ\text{C}$ is the calculated change of cell gap. If we compare this value to the slopes of the measured gap deformations of laminates A and B above 0°C as shown in figure 7, we find a reasonable agreement with the measured data (0.611 $\mu\text{m}/^\circ\text{C}$, 0.511 $\mu\text{m}/^\circ\text{C}$).

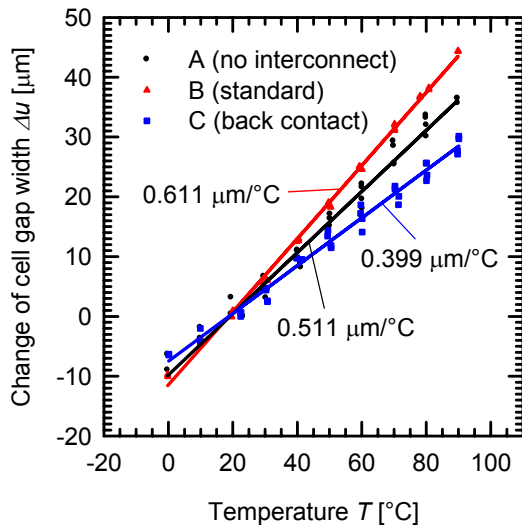


Fig 7: Slope of change in gap width for all three laminates determined by linear regression of data above 0°C.

If we want to fill the gap with a material that matches the empty gap deformation as calculated above, the CTE of the material has to be in the range of $352 \times 10^{-6} \text{ 1/K}$ according to this simple approach. This value is factor 10 to 20 higher than the materials that are suitable for electric interconnection. According to this model it is therefore not possible to realize a stress free interconnection of under these geometrical circumstances and with these material properties.

The simplified calculation above has been restricted to temperatures above 0°C. The reason is, that the encapsulating polymer reaches its glass transition at that temperatures below 0°C. Falling below that temperature region the polymer begins to harden resulting in a much stiffer material behaviour (around 3 orders of magnitude)

in the glassy state. We observed this typical material behaviour in a dynamic mechanical analysis of the EVA. Figure 8 shows the mechanical stiffness in form of the shear storage modulus. Consequently, the assumption of a negligible influence from the polymer in the theoretical investigation above does not hold true for low temperatures.

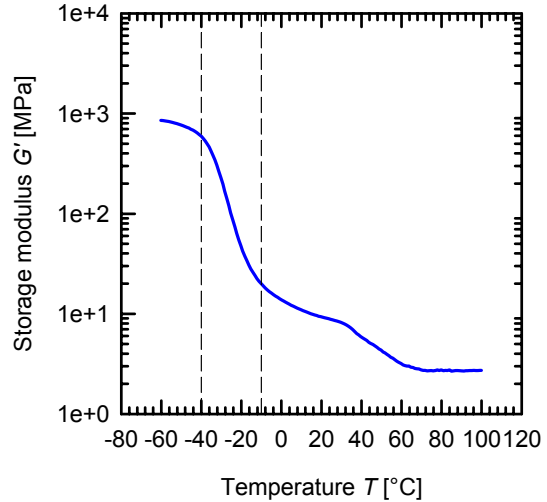


Fig 8: The mechanical stiffness of EVA measured by a dynamic mechanical analysis. The shear storage modulus shows a step of 2 orders of magnitude when falling below -10°C.

CONCLUSIONS

We demonstrated the use of digital image correlation with a stereo camera system for the thermomechanical measurement of solar cells in photovoltaic laminates. A measurement through the window of a climate chamber and a transparent back sheet of the laminate allows full field measurements of the speckled rear sides of the solar cells. The gap between two neighbouring crystalline silicon solar cells opens up when the temperatures increase and shrinks when the temperatures are lowered. Above 0°C the gap deformation is measured to be 0.611 $\mu\text{m}/^\circ\text{C}$ for a standard interconnected laminate (B), 0.511 $\mu\text{m}/^\circ\text{C}$ for a non-interconnected cell string (A) and 0.399 $\mu\text{m}/^\circ\text{C}$ for a laminate with H-shaped back contact interconnectors. A simplified calculation of the cell gap deformation is presented leading to a value of 0.71 $\mu\text{m}/^\circ\text{C}$ for non-interconnected laminated cells which is in reasonable agreement with the measured data. According to this calculation stress-free interconnections are not possible under the restriction of the fixed geometry and the use of common laminate materials. Less steep slopes of the gap deformation measurements are found at low temperatures which correlates well with the glass transition of the EVA where the polymeric material becomes stiffer by 3 orders of magnitude. The digital image correlation is well suited for validation experiments to compare the thermomechanics in laminates to solutions from simulation models as well as the evaluation of new interconnection techniques.

Acknowledgments

The authors like to thank P. Mäckel from isi-sys for the support concerning the measurement system, F. Thiebaut and A. Tietze for the experimental assistance as well as I. Kunze and S. Blankemeyer for the sample preparation.

REFERENCES

- [1] Van Driel W D, Zhang G Q, Fan X J. Thermo-mechanics of integrated circuits and packages. In: Zhang G Q, van Driel W D, Fan X J, editors. *Mechanics of Microelectronics*, New York: Springer, 2006
- [2] Suhling J C, Lall P. Electronic packaging applications. In: Sharpe W N Jr, editor. *Springer handbook of solid experimental mechanics*, New York: Springer, 2008
- [3] P.Lall, D. Iyengar, S. Shantaram, P. Gupta, D. Panchagade, J. Suhling, Feature extraction and health monitoring using image correlation for survivability of leadfree packaging under shock and vibration, *International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Micro-Systems, EuroSimE 2008*.
- [4] P.Bing, X. Hui-min, H. Tao, A. Asundi, Measurement of coefficient of thermal expansion of films using digital image correlation method, *Polymer Testing(2008)*, doi:10.1016.
- [5] Zhang D, Arola D D. Applications of digital image correlation to biological tissues. *Journal of Biomedical Optics* 2004; 9(4): 691-699
- [6] Orteu J-J. 3-D computer vision in experimental mechanics. *Optics and Lasers in Engineering* 2009; **47**: 282-291
- [7] Sutton M A. Digital Image Correlation for Shape and Deformation Measurements. In: Sharpe W N Jr, editor. *Springer handbook of solid experimental mechanics*, New York: Springer, 2008
- [8] Eitner U, Koentges M, Brendel R. In-situ measurement of thermomechanical deformations of photovoltaic laminates using digital image correlation, *Composite Science and Technology*, submitted June 6, 2009