High Precision Placement of Solar Cell Assemblies on large Base Plates for Concentrator Photovoltaics

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Abstract

Photovoltaic concentrator applications use an optical system to concentrate sunlight on solar cells. A high concentration factor is necessary in order to reduce the size of the solar cells and hence to lower the costs for concentrator systems. The precise handling of the small solar cells calls for a high precision micro assembly process for base plate manufacturing. In this paper, the accuracies of the equipment and the processes used for high precision assembly of module base plates are analyzed. The sensitivity of the concentrator module to lateral dislocations of the cells is investigated in order to quantify the accuracy needed for the assembly process. The manufacturing equipment was characterized with respect to repeatability and to absolute accuracy. A repeatability of $\pm 6 \mu m$ for the X-axis and $\pm 15 \mu m$ for the Y-axis has been determined. The process accuracy is better than $\pm 60 \mu m$, depending strongly on the measurement methods used for calculating the position errors.

Keywords: micro assembly, accuracy, concentrator photovoltaics

1. Introduction

During the last years, concentrator photovoltaics (PV) has been the subject of intensive research and development efforts, and the introduction of the technology into the market has been started \cite{1,2,3}. One of the most outstanding advantages of concentrator PV is that only a very small fraction of the total solar module has to be covered by solar cells. The concentration ratio represents the geometrical ratio of the active solar cell area to the aperture area of the optical system. At high concentration ratios, the fraction of solar cell area needed per module area becomes small enough so that the use of more expensive high efficiency cells becomes economically attractive. Multi-junction cells based on III-V compound semiconductors with record cell efficiencies of up to 39.0\% at a concentration ratio of 236 \cite{4} may be used. Up to the present, modules with concentration ratios between 2 and 1000 have been manufactured. Any module with high concentration ratio has to be mounted on a tracking system to ensure proper positioning of the module to the sun.

2. The FLATCON\textsuperscript{®} system

At the Fraunhofer ISE, high concentration modules with an all-glass module body and Fresnel lenses have been developed (Fig. 1). This concept of module design is abbreviated with the acronym FLATCON\textsuperscript{®} (Fresnel Lens All-glass Triple-Cell CONcentrator). FLATCON\textsuperscript{®} type modules are based on monolithic triple-cells maximizing the part of the solar spectrum used for photoelectric conversion. These cells are made by epitaxial growth of more than 30 semi-conducting layers and feature three p-n-junctions with different bandgaps, each specialized in converting a certain range of the solar spectrum (see e.g. \cite{5}).

Fig. 1. Concentrator module with FLATCON\textsuperscript{®}-technology. The module is filled with smoke to visualize the cone of light that originates from each Fresnel lens.

Due to the high heat flux resulting from the high concentration ratio of 500, the solar cells need to be mounted on heat sinks in order to keep the cell temperature low. This is important because with higher cell temperature the overall conversion efficiency of the cell decreases \cite{6}. Therefore, the cell is mounted on a 29 x 29 mm\textsupersq cm copper heat sink. The back side of solar cell is die-bonded to the main copper layer using silver-filled epoxy adhesives. The heat sink also provides a second metallic layer which is electrically isolated from the main copper layer. This second layer is connected to the front bus of the solar cell with bonded gold wires \cite{7}. In order to protect the solar cell from reverse bias caused by partial shading, a bypass diode is placed on each heat sink and connected to the cell. The complete sub-unit consisting of the heat sink, the solar cell, and the bypass diode is termed “solar cell assembly” (Fig. 2). These solar cell assemblies are mounted on a glass base plate and connected in series with aluminium wire bonds.

Currently, two sizes of modules have been developed: One with 48 solar cell assemblies in a 4 x 12 configuration and one with 150 solar cell
assemblies in a 10 x 15 configuration.

![Fig. 2. Components of a FLATCON®-Module.](image)

One of the most critical determinants for module efficiency is the position accuracy of the cell. The position of the cell must be matched with the focus spot of the corresponding Fresnel lens. However, perfect alignment cannot be achieved. There are several factors in the tolerance chain that determine the total displacement of the focus point:
- the lens production process
- the position accuracy of the solar cell assemblies on the base plate
- the orientation of the lens panel in relation to the base plate
- the mounting of the modules on the tracking system
- the accuracy of the tracking system with respect to elevation and azimuth

The sensitivity of a module to these sources of inaccuracy is closely linked to the acceptance angle of a module, which is defined as the angle of the module to the sun where 90% of the maximum power output is delivered. As shown in [8], the short-circuit current (Isc) can be used as an adequate measure of the sensitivity to angular deviation. The sensitivity to lateral displacement in the plane of the module surface, e.g., caused by low assembly accuracy, can be calculated by the sensitivity to angular deviation (Fig. 3).

![Fig. 3. Sensitivity of FLATCON®-modules to lateral or angular deviation for different lens types and solar cell dimensions. The cell parameters are taken from the 2 mm cell in [9].](image)

The objective of this paper is to evaluate the positioning process of the solar cell assemblies on the base plate. Therefore, it is important to specify a placement accuracy, mandatory or desirable for the assembly equipment. Due to the nonlinearity of the lateral displacement sensitivity as depicted in Fig. 3, the effect of a given placement inaccuracy during the production process depends largely on the amount of inaccuracy induced by all other processes that contribute to the tolerance chain. For example, if all other elements of the tolerance chain together cause a 300 µm lateral displacement, the effect of a 100 µm assembly inaccuracy leads to a decrease in Isc by 1.4%. If the other errors cause 700 µm lateral displacement, this figure amounts to 3.5%.

2. The assembly process

The nominal positions of the solar cell assemblies on the base plate during the assembly process are defined by the design of the lens panel and the lens production process. The lens panels used consist of 48 or 150 seamlessly packed Fresnel lens elements, each having a quadratic aperture area of 40 x 40 mm². Therefore the nominal positions of the focus points (which are also the nominal positions for the cell) are located in a grid pattern with a spacing of 40 mm. Due to imperfections in the production process of the master lens plate, these positions can vary in the range of ±300 µm. The nominal positions of the solar cells are calculated from the measured focal points of a master lens plate and are delivered to the base plate assembly equipment.

The most important step during the whole assembly process of the module base plate is the mounting of the solar cell assembly on the glass base plate. This step is particularly challenging because a high absolute accuracy is required on a large working area in order to build cost attractive large-sized modules. To accomplish this process, a micro assembly system from Manz AG is deployed. The system is part of the highly automated production equipment which has been installed in 2006 at the Fraunhofer ISE. This production facility is used to test different base plate designs, assembly processes and materials.

3. Accuracy of the placement equipment

To reach a high accuracy in the positioning process, the micro assembly machine has been equipped with a vision system to recognize the center of the solar cell. The vision system is based on a high magnification camera integrated in the placement head.

To test the repeatability and the absolute position accuracy of the axes and the vision system, a 400 x 600 mm² calibration plate with 150 fiducials, arranged in a square 40 mm grid, was used (Fig. 6).

![Fig. 4. Illustration of the fiducial marks on the calibration plate.](image)

The characterization of repeatability and accuracy of the pick & place process is based on the process capability index $c_{pk}$ (see e.g. [10]), which is calculated using Eq. 1:

$$c_{pk} = \frac{USL - LSL}{6\sigma} \left(1 - \frac{|m - \bar{x}|}{(USL - LSL)/2}\right)$$  (1)
with \(USL\): upper specification limit, \(LSL\): lower specification limit, \(\sigma\): standard deviation, \(m\): midpoint of the specification range and \(\bar{x}\): process mean. With the \(m = 0\) and \(c_{pk} = 1\), this equation can be transformed to Eq. 2.

\[
3\sigma + |\bar{x}| = (USL - LSL)/2
\]

(2)

Due to the symmetrical sensitivity of the module to dislocations (see Fig. 3), the USL and the LSL are chosen symmetrically around the ideal position of 0 and the range USL-LSL will be stated in this paper in the form \(\pm (USL-LSL)/2\) (e.g. \(\pm 30 \mu m\)). These values are in the following referred to as “3\(\sigma\)-values”

### 3.1 Repeatability

For testing the repeatability, the micro assembly system was trained to recognize the fiducial marks on the calibration plate and to report the measured positions. The measured values differ from the “correct” nominal values \(P_i\) and are centered around mean points \(P'_i\) (see Fig. 4). The distribution of the measured values around the corresponding \(P'_i\) is shown in Fig. 5, revealing a repeatability value of 6 \(\mu m\) at 3\(\sigma\) for the X-axis and 15 \(\mu m\) for the Y-axis.

![Fig. 5. Distribution of the repeatability error for X- and Y-axis based on 2235 measurements for each axis.](image)

One reason for the higher repeatability error on the Y-axis is the double-drive gantry construction of the micro assembly machine, which needs simultaneously coordinated control of both linear motors.

When measuring the absolute accuracy, the absolute position of a calibration standard in relation to the coordinate system of the machine is not known a priori. If the axes and the vision systems are used to detect the position of the calibration standard (e.g. by recognizing fiducial marks), the errors of this adjustment have impact on the measurement of the absolute accuracy. Therefore, absolute accuracy was measured with two different methods: absolute distance measurements and calculation of a translation/rotation vector that produces the best match between the calibration normal and the measured values.

### 3.2 Absolute distance measurement

In absolute distance measurements the distance \(D_{1,2}\) (see Fig. 4) between two means \(P'_1; P'_2\) of a set of measured points is compared to the nominal distance \(P_1; P_2\). In Fig. 6 the distances in X-direction for each fiducial mark to the first fiducial mark in the same row is plotted, revealing a distance accuracy for the X-axis of \(\pm 13 \mu m\) at 3\(\sigma\). The corresponding value for Y-axis distance accuracy is \(\pm 24 \mu m\) at 3\(\sigma\).

![Fig. 6. Absolute distance accuracy of the distances in X-axis-direction measured from the most right fiducial mark in each row. The positions \(P'_i\) have been calculated by averaging 15 measurements for each mark.](image)

It must be noted that the position accuracy of the calibration plate itself is specified with \(\pm 5 \mu m\). The thermal expansion coefficient of the plate is \(9 \times 10^{-6}\) K\(^{-1}\), resulting in a distance change between the fiducial marks at the edges of the plate of 6 \(\mu m\) per 1°C change in temperature.

### 3.3. Fitting of translation/rotation

Every time a base plate or a calibration plate is put into the machine, its position can only be fixed manually with a repeatability of ~0.5 mm. Therefore, raw position data can not be used for calculating the absolute accuracy without compensation for the unknown translation and rotation of the measured plate. If a plate changes its place and orientation due to a translation \((u_x, u_y)\) and a rotation \(\alpha\), the new positions \((x'_i, y'_i)\) of all points on the plate can be calculated from \((x_i, y_i)\) as stated in Eq. 3 and Eq. 4:

\[
x'_i = \sqrt{x_i^2 + y_i^2} \cdot \cos(\alpha + \arctan(y_i/x_i)) - u_x
\]

(3)

\[
y'_i = \sqrt{x_i^2 + y_i^2} \cdot \sin(\alpha + \arctan(y_i/x_i)) - u_y
\]

(4)

A nonlinear solver was used to calculate a translation/rotation that minimizes Term 5:

\[
\sum_{i=1}^{15} \sqrt{(x'_i - x_i)^2 + (y'_i - y_i)^2}
\]

(5)

with \(x_i\) and \(y_i\) being the nominal positions of the fiducial marks on the measured plate. Using this method, typical absolute accuracies for one measurement run are 20 \(\mu m\) for the X-axis and 17 \(\mu m\) for the Y-axis.

With this method, errors in absolute accuracy may be indicated only with half of their absolute value. However, during the module assembly later in the process chain, the lens panel is adjusted through mounting it with a translation/rotation providing the best fit between focus points and cells. So this method can be used as a valuable indicator on accuracy realized on a completed module level.

### 4. Process accuracy

For determining process accuracy, three base plates with 48 solar cell assemblies on each plate have been manufactured and measured. For measuring the process accuracy the micro assembly machine itself was used. This eliminates mistakes through different
ambient temperatures and allows to measure immediately after the assembly, yet the repeatability and the absolute accuracy of the machine itself (see chapter 3) have to be taken into account when interpreting the following process accuracy figures.

For determining the accuracy of the placement process, the base plate was measured directly after assembly without releasing the clamping of the base plate. Therefore, no rotation/translation of the plate has to be considered and a comparison can be made between raw data interpretations (differences between nominal and actual positions), distance measurements (see chapter 3.2) and translation/rotation fitting (see chapter 3.3). The results for these three measurements types are stated in Table 1.

Table 1. 3σ-values for differences between nominal and effective positions.

<table>
<thead>
<tr>
<th>Plates</th>
<th>Raw Data</th>
<th>Distance</th>
<th>Fit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X [µm]</td>
<td>Y [µm]</td>
<td>X [µm]</td>
</tr>
<tr>
<td>Plate1</td>
<td>64</td>
<td>41</td>
<td>38</td>
</tr>
<tr>
<td>Plate2</td>
<td>46</td>
<td>54</td>
<td>41</td>
</tr>
<tr>
<td>Plate3</td>
<td>51</td>
<td>48</td>
<td>30</td>
</tr>
<tr>
<td>All 3 Plates</td>
<td>54</td>
<td>49</td>
<td>39</td>
</tr>
</tbody>
</table>

As no significant changes in position accuracy compared to table 1 can be found, it is concluded that the current process of UV-curing does not induce significant additional position errors.

5. Summary

The accuracy of the assembly process for base plates is an important factor for high module efficiencies. The very large working area imposes challenging requirements on the assembly equipment. It has been shown that a 100 µm error in assembly accuracy induces a short circuit current loss in the typical range of 1.4% to 3.4%. Absolute accuracy of the equipment used for base plate assembly was determined to be ±13 µm for the X-axis and ±24 µm for the Y-axis at 3σ using a calibration plate. Process accuracy was found to be better than 60 µm at 3σ, depending significantly on the method of determining absolute accuracy.

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References


