ACOUSTIC AND ELECTRIC DIAGNOSTICS OF DEGRADATION IN PV CELLS AND MINI-MODULES

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ABSTRACT: The aim of this work was to find the possibility to estimate the influence of forced ageing on the properties of photovoltaic modules. We have measured sound velocities in crystalline silicon PV modules before and after forced ageing. The commercially available mini-modules consisted of three high efficiency c-Si cells connected in series. Investigation of electrical properties was performed also before and after accelerated ageing under increased temperature and PID. It was found that forced ageing strongly affects the sound velocity of the complete modules. It was shown that impedance spectroscopy measurement and characterization is an important tool to reveal the degradation of the solar cells due to high voltage stress and increased temperature stress.

Keywords: Accelerated Ageing, Acoustic Transmission, Complex Impedance, Potential Induced Degradation

1 INTRODUCTION

With the increased use of photovoltaic electricity generation surveillance the of degradation becomes important in order to prevent a drop out of parts or the whole power plant. Currently the methods of degradation monitoring focus on the electrical performance of the cells themselves. IR and electroluminescence imaging are widely in use [2,3]. Much less attention is paid to changes of the rest of the modules, like encapsulation though in several cases like the potential induced degradation effect they were found to be responsible for cell degradation [4].

Sound velocity measurements are a well established technique for material fatigue and failure recognition [5].

Among the electrical measurements on PV cells and modules complex impedance dependences offer valued indication of equivalent circuit elements which finally leads to determine the performance of illuminated solar cell and module [6] and estimate degradation processes due to ageing [7].

2 EXPERIMENTAL

The acoustic and ac electric measurements have been performed on commercially available small PV modules assembled from 3 series connected 6×6 mm² monocrystalline cells [1].

2.1 Acoustic transmission

The set up for the acoustic transmission measurements was based on the sonic viewer from Oyo corporation, model 5210. For the experiments two matched - in frequency and size - piezo transducers for shear wave generation/reception were used. The resonance frequency was 33 kHz. The circular surface had a diameter of 31.3 mm. Originally the instrument was intended for sound velocity measurements of geological samples. It consists of a precise time base, a high voltage

Figure 1: Plots of the recorded sound waves in the time domain (left graph) and the frequency domain (right graph)
In our case that is $154 \text{ mm}^2 / 770 \text{ mm}^2 = 0.2$. Due of the sample’s surfaces to the transducer’s and receiver’s observable attenuation should arise solely from the ratio Furthermore absorption and internal reflection on about 10 times the sample’s actual thickness of 1.8 mm. 

In our case the sample’s area is smaller than the transducer’s area and the thickness is much smaller than the wavelength of the sound wave. For this reason an excitation which is perpendicular to the direction of propagation was chosen. In order to estimate how suitable the set up could be for our measurements model calculations with a copper sample of the module’s dimensions are made. The sound velocity of 2325 m/s for shear waves in copper was taken from the literature [8]. For a frequency of 33 kHz the sound wavelength, $\lambda_0$ in copper is calculated to be 70 mm. The quarter wavelength condition for destructive interference is still about 10 times the sample’s actual thickness of 1.8 mm. Furthermore absorption and internal reflection on boundaries are expected to be negligible. Therefore the observable attenuation should arise solely from the ratio of the sample’s surfaces to the transducer’s and receiver’s surfaces. In our case that is $154 \text{ mm}^2 / 770 \text{ mm}^2 = 0.2$. Due to the increased distance between transmitter and receiver the sound wave will be received with delay. For 1.8 mm copper the received signal will be delayed for ~0.8 µs compared to the observation with directly coupled transducers.

Our experimental observation with one of the mini-modules resulted in an attenuation of the amplitudes of 0.18 and a time delay, $\Delta t = 0.96 \mu s$. Both values are in agreement with our expectation from the model calculation for copper. The overall shear wave sound velocity for the composite structure of the module was calculated to be about 1900 m/s. The time delay was directly measured by overlaying the two received curves in the time domain. The left graph in Fig. 1 shows the plots enlarged around a zero crossing of the amplitudes. The black line corresponds to the measurement with transmitter and receiver face to face and the red line with the inserted module. The right graph shows the amplitudes of both signals in the frequency domain together with an inset of the experimental arrangement.

2.2 Forced ageing of minimodule

In order to find out how sensitive the acoustic transmission measurement can be to physical changes of the module a time series with one module exposed to elevated temperatures was made. Beside the acoustic transmission measurement the mass, thickness variations and the electroluminescence (EL) was determined in time increments of days during the sample’s heat treatment.

A temperature controlled drying unit was used to keep the sample at a constant temperature of $87 \degree C$ under ambient air conditions.

Monitoring the weight of the sample is a fast and easy indicator of changes within the module due to heating. The first time when the sample was weighted was one year ago and a mass of $m = 514.2 \text{ mg}$ was found. Immediately before the module was transferred to the heating chamber $m = 514.45 \text{ mg}$ was measured. The sample’s thickness was measured in order to derive the sound velocity from the transfer time of then acoustic shear wave through the sample. The thickness in the centre of the module was determined with a profilometer from Heidenhain with a resolution of 1 µm. A thickness of 1.838 mm was measured prior to the heating treatment. The EL intensity of the module was recorded in order to observe whether changes in the cell’s performance take place during the heat treatment. A glass fibre bundle with a diameter of ~3 mm was placed above the centre of each of the three individual cells in the module. The emitted EL intensity was detected by an InGaAs photodiode (DET10C of Thorlabs). The module current was varied from 1 mA up to 35 mA in increments of 2 mA. With respect to the short circuit current, $I_{sc}$ of ~15 mA under STC [1] the current variations cover a range from 0.1 – 2 x $I_{sc}$. The signal of the middle cell before the heat treatment was taken as reference for all subsequent recordings.

2.3 Electrical performance

Electric parameters of PV module are sensitive to changes mainly under PID treatment. Experimental mini-modules were stressed under 1000 V dc (short circuited top and bottom electrodes against grounded auxiliary electrode) and at temperature 80 °C for 48 hours. The influence of PID was evaluated by impedance measurements and the difference in the state before and after the degradation determined.

<table>
<thead>
<tr>
<th>Date/Time</th>
<th>Mass [mg]</th>
<th>Thickness [mm]</th>
<th>Time-Delay [µs]</th>
<th>Velocity [m/s]</th>
<th>EL intensity [a.u.]</th>
</tr>
</thead>
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<tr>
<td>18.8/11:00</td>
<td>514.45</td>
<td>1.838</td>
<td>1.01±0.13</td>
<td>1820</td>
<td>1.00±0.04</td>
</tr>
<tr>
<td>19.8/11:00</td>
<td>511.2</td>
<td>1.834</td>
<td>1.56±0.13</td>
<td>1176</td>
<td>1.01±0.06</td>
</tr>
<tr>
<td>20.8/9:30</td>
<td>510.6</td>
<td>1.821</td>
<td>1.56±0.12</td>
<td>1167</td>
<td>1.01±0.10</td>
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<tr>
<td>22.8/9:30</td>
<td>509.5</td>
<td>1.816</td>
<td>1.73±0.12</td>
<td>1050</td>
<td>1.00±0.06</td>
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<tr>
<td>26.8/9:30</td>
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<td>1.811</td>
<td>1.44±0.07</td>
<td>1258</td>
<td>1.00±0.06</td>
</tr>
</tbody>
</table>

Table 1: Summary of measured module parameters
3 RESULTS AND DISCUSSION

3.1 Acoustic measurements
The results of the time series are summarized in Table I. In Fig. 2 the relative change from the initial values of the measured parameters are plotted. The mass, as well as the measured thickness in the middle of the module, decreases continuously. After one week a reduction of more than one per cent was observed. Within the resolution of our experiment the EL intensity remains unchanged indicating that the heat treatment has no effect on the cells performance. Although the acoustic transmission measurements have a low resolution compared to the other measurements a significant reduction of the sound velocity from 1800 m/s to 1200 m/s was recorded already after one day at elevated temperatures. It seems that the sound velocity responds faster to temperature stress than mass or thickness which are in good correlation with each other. During the time of operation mass as well as module thickness decreases by only 1 per cent whereas the sound velocity reduces for more than 30 per cent. With the exception of about 200 μm crystalline silicon which do not exhibit a resolvable ageing effect of its opto-electrical properties thickness and composition of all other layers in our 1.8 mm thick sample was not known. It is likely that most of the change in the sound velocity is caused by polymers which were used in the module.

Figure 3: Equivalent circuit used for experimental impedance spectroscopy data evaluation

3.2 Electric behaviour under the influence of PID
The electric behaviour of the module is interpreted using equivalent circuit (Fig. 3) proposed in accordance with complex impedance frequency dependencies through standard simulation techniques. Constant phase element P1 was included for the best fitting and current

Table II: Equivalent circuit elements for sample before and after PID treatment at 1347 mV DC.

<table>
<thead>
<tr>
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<th>C1 [F]</th>
<th>R1 [Ω]</th>
<th>R2 [Ω]</th>
<th>R3 [Ω]</th>
<th>P1 [F.s^{(n-1)}]</th>
<th>n [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before PID</td>
<td>2.877E-07</td>
<td>15.430</td>
<td>175.97</td>
<td>21.701</td>
<td>5.0839E-07</td>
<td>0.84861</td>
</tr>
<tr>
<td>After PID</td>
<td>1.3574E-07</td>
<td>15.742</td>
<td>233.16</td>
<td>58.873</td>
<td>3.8374E-07</td>
<td>0.78903</td>
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transport processes estimation. Complex impedance, real and imaginary parts, was measured under bias 1347 mV and the results are presented in Fig. 4. The values of equivalent circuit elements are presented in Tab. II.

4 CONCLUSION

Complex impedance technique has found application in electrochemistry and it is also capable and giving relevant results in estimation of PV module behaviour, either the solar cells themselves or total module layered structure which includes semiconductor, insulator and metallic parts. The changes due to high voltage stress were clearly distinguished using complex impedance measurements and the elements of equivalent circuit calculated using simulation technique. Our results show that the sound velocity was highly sensitive to changes in the mechanical properties of the module. No further interpretation of the results we have made can currently be given. However the experiments were primarily intended as a proof of our concept for the usability of acoustic diagnostics as a simple inspection tool during module maintenance.

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References