STRESS MEASUREMENT BY X-RAY DIFFRACTION IN MULTICRYSTALLINE SILICON SOLAR CELLS

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ABSTRACT

Residual stresses in multicrystalline silicon solar cells has become a problem of growing importance, especially in view of silicon wafer thickness reduction. Without increasing the wafer strength, this leads to a high fracture rate during subsequent handling and processing steps. The most critical processing step during the manufacture of screen-printed solar cells is the firing of metallic contacts. In this work we evaluate the development of mechanical stresses in metallic contacts (Al, Ag and Al/Ag bus bars) with respect to different processing steps. For this purpose we combine X-ray diffraction (XRD) stress measurements, cell bowing measured with a laser scanning device and in-situ bending tests. It was found that the Al back contact layer represents a very porous/loose microstructure, which does not affect the mechanical stability of the solar cell. It was also found that the thickness and uniformity of the eutectic layer are the most important factors influencing the bowing of a complete solar cell. Furthermore, residual stresses and stresses developing during cell bending in Ag, Al/Ag bus are measured and discussed in detail in this work.

1. INTRODUCTION

Nowadays solar cells and solar panels represent a complex interconnected system with different interfaces in a multi-layer/multi-stacked package. Residual stresses are formed within the cell due to mismatch of thermal expansion coefficients and different mechanical behavior of the materials used in the metallic contacts and solder interconnections. Residual stresses have a great effect on the mechanical properties of the materials, such as fracture, wear and friction. Cracking of solar cells has become one of the major sources of solar module failure. Therefore, it is not only important to investigate the electrical properties of silicon solar cells but also the stress state development during the manufacturing of solar cells. In order to take in account the effect of the residual stress during the design and processing of solar cell, the actual level and sign of stress in the material has to be determined. This research gives a deeper understanding on metallic contact build up and provides concrete information regarding the stress distribution in solar cells. The resulting data can be used to enhance production yields, improve cell reliability and establish mechanical criteria that lead to a reduction in cell costs. In this work several aspects related to solar cell processing conditions and metallization are described in relation to residual and bending stresses.

2. EXPERIMENTAL CONDITIONS

Residual stress measurements were performed on rectangular (10x30 mm) neighboring multicrystalline (MC) silicon solar cell specimens which were laser cut from complete solar cells. Stresses in metallic layers of MC-silicon solar cells were measured using XRD, where the $\sin^2\psi$ stress evaluation method was used to deduce the stress from the slope of *d* (spacing of diffracted planes) vs. $\sin^2\psi$ [1]. XRD was chosen among other non-destructive investigation techniques because it is the most accurate and best developed method, which is capable of high spatial resolution, on the order of millimeters and depth resolution on the order of microns, as well as it can be applied to a wide variety of samples geometries.

To investigate the effect of the maximum firing temperature of the Al back contact, three neighboring wafers were processed with identical conditions, but with different peak temperatures, *i.e.* 750, 850, and 950 ^{o}C.

In order to examine the influence of aluminum layer thickness on the residual stresses of the cells, two different cells with 20 and 40 microns Al layers were investigated (commercially available Al paste A was used).

Measurements of the amount of bowing that result from metallization were made by an optical method over the full length of the solar cell (156 mm), using a Quick Vision Mitutoyo system. Aluminum porous layer was partially removed with Ar ions by using a Gatan precision ion polishing system, normally used for Transmission electron microscopy, in order to measure residual stresses in the eutectic layer.

In order to exclude a possible effect of surface roughness on the stress measurement that could arise due to the limited X-ray penetration depth in Ag, the silver surface was gently polished down to 1 μm.

Scanning electron microscopy (SEM) was used to analyze the surface and cross section morphology of solar cells. XRD was also used to examine the phase and element composition.

Specifically for this work, a bending device was built to fit inside the X-ray goniometer of a Bruker D8 diffractometer with Eulerian cradle and parallel beam optics (assuring that bending of the sample does not affect the diffraction), using CoKα wavelength. (Figure 1). Different in-situ bending and XRD stress analysis experiments were performed.

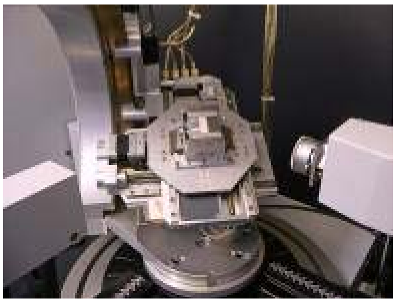


Figure 1. In-situ bending clamping device for XRD
a) Bending device with solar cell sample
b) Bending device inside the diffractometer

3. RESULTS

3.1. RESIDUAL STRESSES IN ALUMINUM REAR SIDE AND SILVER FRONT SIDE CONTACTS

From our previous investigations in was found that aluminum layer has a complex composite-like microstructure, consisting of three main components: 1) spherical (3 - 5 µm) hypereutectic Al-Si particles, surrounded by a thin aluminium oxide layer (150-200 nm); 2) a bismuth-silicate glass matrix (3.3%) 3) pores (14%) [2]. It is know that when fired, aluminum layer creates large solar cell bowing [3], however it is not entirely clear what is the effect of aluminum porous part on strength of solar cells. X-ray stress measurements were conducted on two solar cell samples with different thicknesses of aluminum back contact. Results showed that residual stresses in the porous part of the Al back contact layer are very low, *i.e.* in the range of 10 MPa (Figure 2, Table 1). It was also found that a 20 µm thick Al layer shows higher stresses than a 40 µm layer (the X-ray information depth in Al is equal to ~20 µm). This result could indicate that Al porous part of the rear side contact is very loose and the major part of the solar cell bowing is generated by the reaction Al-Si eutectic layer. It should be pointed out that residual stresses were found to be equal in longitudinal and transverse directions, for both Al and Ag layers.

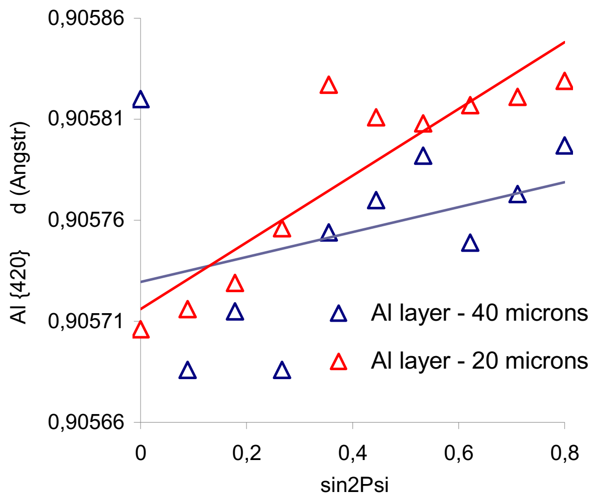


Figure 2. Effect of Al layer thickness on Residual stresses (Information Depth - 20µm)

Table 1. Residual stresses in Al layer

Al layer thickness (µm)	Stress (MPa)	Stress error (MPa)
20	10	1.8
40	3	3.4

In order to confirm this hypothesis a part of the aluminum layer was gradually removed, resulting in a cross section shown in Figure 3. The stresses in the removed layer, and as thus in the eutectic layer, were found to be -30 MPa (Figure 4). However, this value is not representative for the entire eutectic layer, because the scan was partially covering the edges of the porous part of the Al layer. Further investigations including more precise and gentle layer removal methods are required to obtain an actual stress value for the Al-Si eutectic layer.

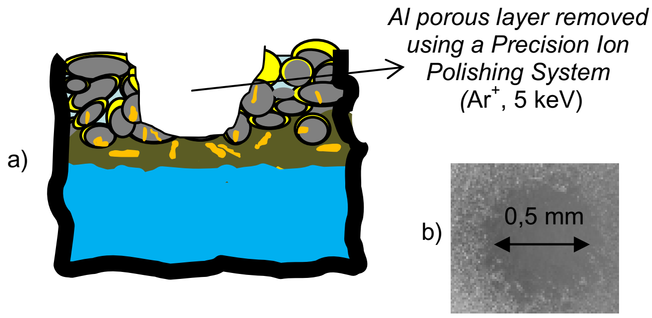


Figure 3. Removal of Al porous layer
a) Draft cross section of the layer
b) Resulting “hole” in the porous part of the Al layer

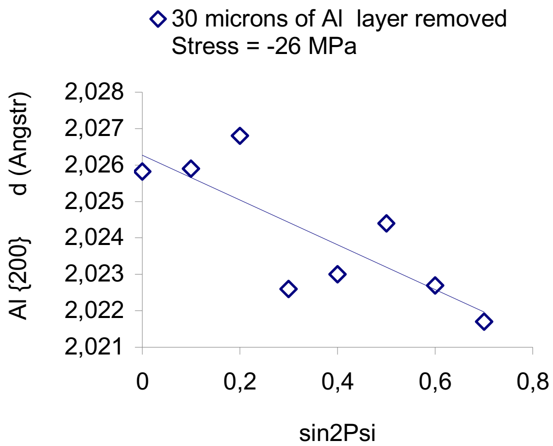
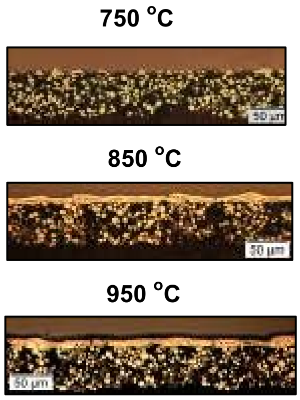


Figure 4. XRD stress result for the eutectic layer (sample with removed Al layer)

Specimens with different firing temperatures of the Al back contact, and as a result with different thicknesses of the eutectic layer, showed that higher firing temperatures lead to larger amounts of cell bowing (Figure 5). The bow increase could only be explained by the increased thicknesses of the eutectic layer, because Al layer thicknesses remained constant for all the samples. XRD pattern of Al layer fired at different temperatures showed that there is an increased amount of Si in Al layer (with increasing firing temperature), indicating on a higher diffusion of Si inside liquid Al particles (Figure 6).

Furthermore, XRD stress measurements in Al layer showed that there is only a minor stress increase with increasing the firing temperature (Figure 7). This increase could be a result of higher amount of Si phase inside Al particles, leading to a higher degree of aluminum deformation. Nonetheless the low value of stresses there is a clear increase of the amount of bowing, which could result from the eutectic layer itself, rather than from the porous part of aluminum layer. Thus, it can be concluded, that both the thickness and uniformity of the eutectic layer can be considered as the most important parameters controlling mechanical stability of silicon solar cells.



Firing temperature (°C)	Amount of bowing (mm)
750	0.48
850	1.40
950	1.80

Figure 5. a) Effect of maximum firing temperature on microstructure of Al back contact layers, showing different thicknesses of the eutectic layer b) Resulting amount of bowing.

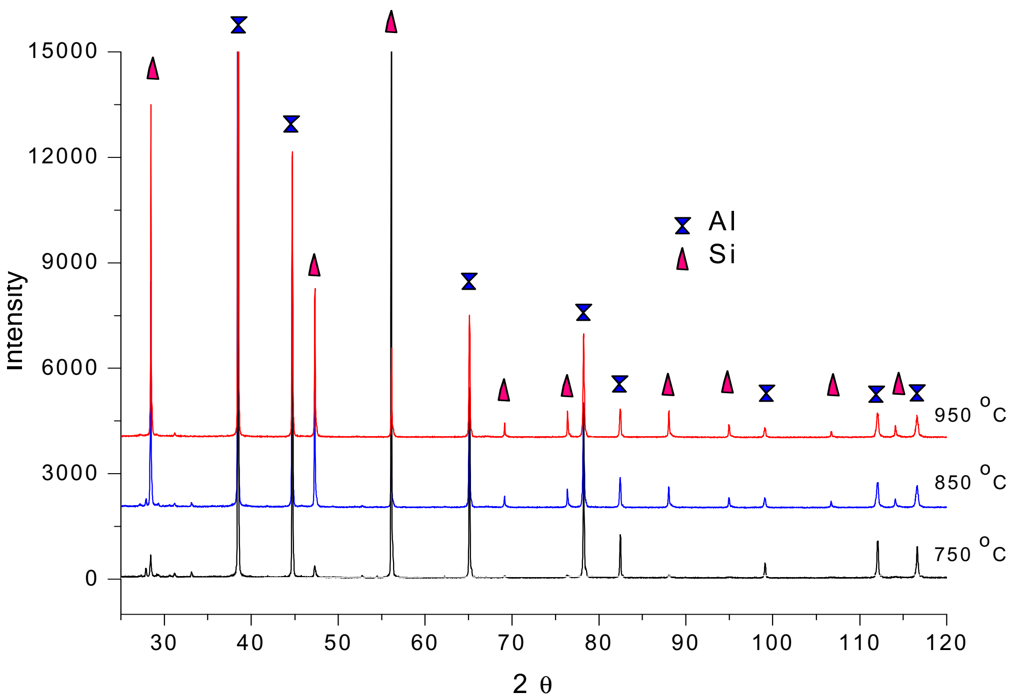
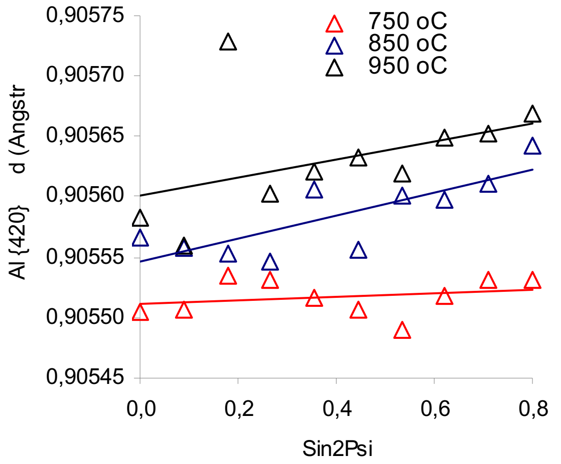


Figure 6. XRD pattern of Aluminum layer fired at 750, 850 and 950 °C



Firing Temperature (°C)	Stress (MPa)	Stress error (MPa)
750	0.8	1
850	5.5	1.5
950	4.5	3

Figure 7. Effect of firing temperature (eutectic layer thicknesses) on residual stresses (Information Depth - 40µm)

XRD stress measurements were also performed on silver front contact and Ag/Al bus bars, Figure 8.

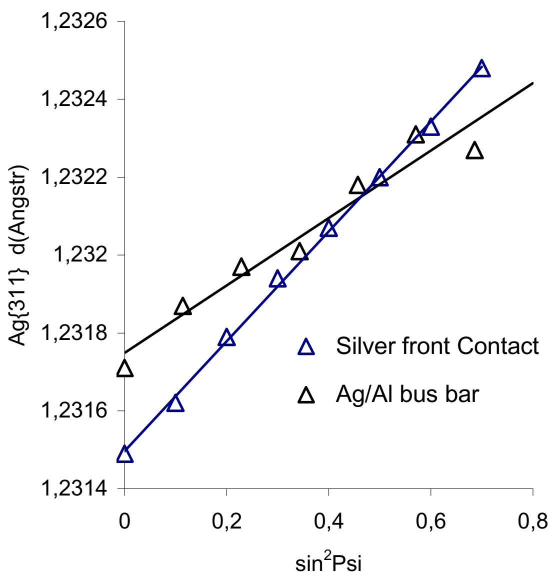
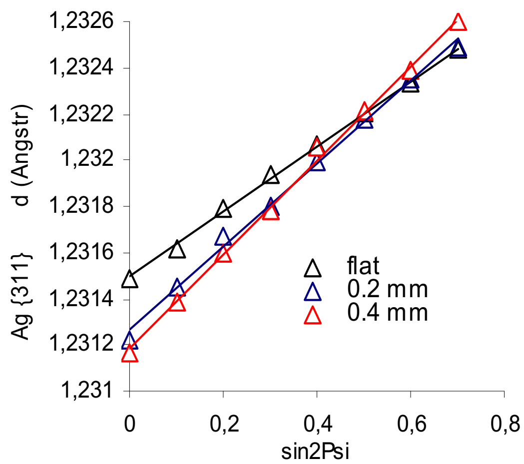


Figure 8. Residual Stresses in Silver front contact and Silver Bus bar (Penetration Depth ~ 2 µm)

The stress in the Ag/Al bus bars was found to be lower (41 MPa), compared to the stress in the Ag front side contact (70 MPa). This could be explained by the different composition of silver bas burs, containing aluminum phase.

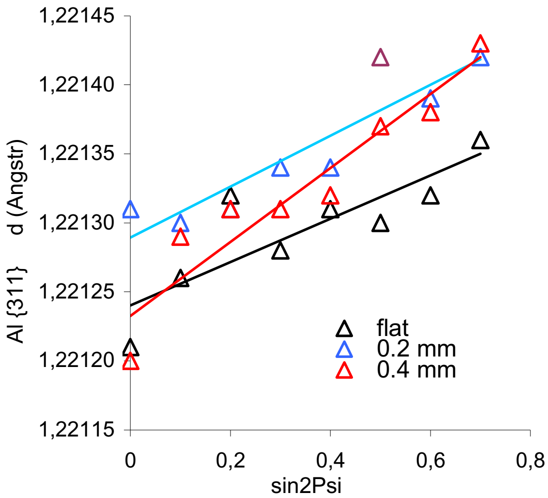
3.2. STRESS MEASUREMETNS IN COMBINATION WITH BENDING TESTS

An in-situ loading of the Ag layer showed an increase in bending stresses (Figure 9), indicating that it is possible to measure bending stresses by X-ray diffraction using an in-situ bending clamp. The maximum amount of stresses in Ag layer was to be 110 MPa for the deflection of 0.4 mm.
In-situ loading of the Al layer using the bending device installed inside the diffractometer was performed in order to measure bending stresses in the porous part of Al layer. As can be seen from Figure 10, bending of aluminum layer did not result in any significant stress increase in the Al porous layer. These results further indicate that the porous part of Al back contact is too loose to have any residual or bending stresses and as result it cannot give any contribution to the fracture strength of solar cells. For the follow up experiments a more precise bending clamp, capable of in situ load and displacement measurements will be used. The obtained data could be compared with the previously performed bending tests [4].
The obtained stress data will be used in a multiscale model and based on the results it should be possible to find a connection between metallization processing conditions, paste microstructures and mechanical stresses.



Sample Deflection (mm)	Stress (MPa)	Stress error (MPa)
0	70	1
0.2	90	2.3
0.4	110	1.9

Figure 9. Bending stresses in Ag front contact



Sample deflection (mm)	Stress (MPa)	Stress error (MPa)
0	7	1.8
0.2	8	1.5
0.4	11	1.6

Figure 10. Bending stresses in Al rear side contact

CONCLUSIONS

The residual mechanical and bending stresses of multicrystalline silicon cells were investigated using X-ray diffraction technique, bowing and bending tests. The study showed that:

- The thickness of the eutectic layer as well as the uniformity of the aluminum back contact layer can be considered as the most important parameters controlling mechanical stability of silicon solar cells.
- There is a correlation between maximum firing temperature, bowing and residual stresses of solar cell, *i.e.* the higher the firing temperature the higher the residual stresses and the bowing.
- The residual stress in the Ag/Al bus bars was found to be lower (41 MPa), compared to that in the Ag front side contact (65 MPa).
- It was found that it is possible to measure bending stresses by X-ray diffraction using an in-situ bending clamp specially designed for thin solar cell specimens. The resulting data gives valuable information about the stress state development during different processing steps of multicrystalline silicon solar cells.

The X-ray diffraction technique, in combination with bow measurements and bending tests, proved to be a powerful non-destructive qualitative and quantitative experimental technique that provides information about fracture behavior and stress states of silicon solar cells.

REFERENCE

[1] Withers PJ, Bhadeshia HKDH, Overview: Residual Stress, Part 1—Measurement Techniques, Materials Science and Technology 17, 2000, pp. 355.

[2] V.A. Popovich, M. Janssen, I.M. Richardson, T. van Amstel and I.J. Bennett, Microstructure and mechanical properties of aluminium back contact layers, Solar Energy Materials and Solar Cells, Volume 95, Issue 1, January 2011, pp. 93-96.

[3] M. Hilali, Understanding and development of manufacturable screen printed contacts on high sheetresistance emitters for low-cost silicon solar cells, 2005.

[4] V.A. Popovich, A. Yunus, M. Janssen, I.M. Richardson, I.J. Bennett, Effect of silicon solar cell processing parameters and crystallinity on mechanical strength, Solar Energy Materials and Solar Cells, Volume 95, Issue 1, 2011, pp. 97-100.