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Effect of Metallization Condition on Mechanical Strength of Multi Crystalline Silicon Solar Cell

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Abstract. During each processing step of multicrystalline (mc) silicon solar cells production, it requires a good mechanical stability to avoid cell breakage. Therefore, wafers and cells with a good mechanical stability are absolutely important. The cracking of silicon wafer solar cells is one of the major failures of solar module. Hence, it is important to evaluate the mechanical strength of solar cells and influenced factor. The present work focuses on determining the effect of metallization conditions on mechanical strength of multi crystalline silicon solar cells. A 4-point bending method was used to measure the fracture strength and data is statistically evaluated by a Weibull analysis for interpretation of the flaws within the specimen. It was observed that drying temperature at 250 °C provides better results than 350 °C. It was found that the contact formation between metal layer and silicon wafer (i.e. eutectic layer) has a significant effect on mechanical properties of mc-silicon solar cells. Moreover, the mesh sizes of screen printing produce different thickness of metal layer without altering the strength of silicon wafer. It was discovered that the metallization process was responsible to alter the mechanical strength of mc-silicon solar cell. It is also observed that the crack can initiate from the edge and surface defects and propagate along the preferred crystallographic plane. It was found that the edge defects look like more dominant as crack initiation.

1. Introduction

The search for and utilization of new and sustainable energy sources is a new challenge that has emerged at the end of the 20th century. The urge of this challenge is underlined by limited resources of the fossil fuels on the earth and increasing demand for energy production. Solar cell energy is one of the solutions for supplying energy by direct conversion of sunlight or other radiation into electricity based on photovoltaic effect. The photovoltaic (PV) effect is the generation of a potential difference at the junction of two different materials in response to visible or other electromagnetic radiation by generating the electron-hole pairs as charge carriers to produce electricity [1].

The major obstacle using solar cells to generate electricity is too expensive compared to the price of electricity generated by traditional sources. A lot of effort has been put into the field of solar cells to reduce the price of solar electricity to a level that is comparable to conventional electricity. The photovoltaic industry needs to put an enormous effort into optimization of every stage of the photovoltaic manufacturing chain in order to reduce cost. The future research and development of photovoltaic solar cell is aimed to increase efficiency, reduce yield loss, and minimized materials consumption [2]. However, reduction of material consumption leads to thinner wafers, leading to a reduction of the mechanical stability of the wafers and increasing the number of broken wafers. Wafer



breakage is a major problem in the silicon photovoltaic industry, limiting production yield and causing an increase in the final cost of PV modules [3]. This problem is particularly important because the PV industry tries to reduce material usage by decreasing wafer thickness and simultaneously tries to achieve higher cell efficiencies to make the price of solar electricity the same as that for conventional electricity. So, wafers and cells with a good mechanical stability are absolutely important. During each processing step of multi crystalline (mc) silicon solar cells production, the mc-silicon solar cell requires a good mechanical stability to avoid cell breakage

Screen printing is used for the formation of the front and rear contacts of solar cells (metallization). This technique is commercially available, robust, simple, and can easily be automated [5]. The silver paste is forced through a pattern screen by dragging a squeegee across the screen as a result of which the silver paste is forced through holes in the screen print pattern. The Ag powder sinters during firing and causes a good lateral conductivity. The silver particle size used in the screen-printed Ag paste is found to influence the structure of the contact interface. For ultrafine particles, rapid and more complete sintering leads to a more compact and less porous Ag grid above the glass layer [6]. After the screen printing of front and rear sides with Ag and Al, the thick layer of wet metal paste is dried by heating to 250 °C – 400 °C in the oven in order to drive off organic solvent and binder. The electric contacts that are formed between wafer and metal paste are fired simultaneously in the firing furnace with a peak temperature around 850 °C to give reasonable metal resistivity. Consequently, the contacts and conductive layers are imprinted in the cell within a furnace [4,5].

The main purposes of this work are to determine the effect of metallization conditions on mechanical strength of multi crystalline silicon solar cells. Several aspects related to solar cell processing conditions and metallization properties are investigated in relation with mechanical strength.

2. Methods

2.1. Specimen Preparation

Specimen preparation was based on ASTM C 1161-02c; the standard test method for flexural strength of advanced ceramic at ambient temperature [8]. The preparation of specimen started from multi crystalline silicon wafers with dimensions of 155 mm × 155 mm and a thickness of 0.190 mm. The ASTM standard indicates that test specimens must have a span-to-depth ratio (L/d) that produces tensile or compressive failure in the outer fiber under the bending moment, so the dimensions that were used in the testing are based on the higher L/d ratio ($> 60:1$). This goes in good agreement with ASTM recommendation to use a higher L/d ratio for material with lower shear strengths. This wafer was then cut by using a laser beam to the desired dimensions (length (L) = 30 mm, width (b) = 10 mm), as illustrated in figure 1. After laser cutting, the edges of all specimens were grinded by using grinding paper no. 1000, 1200, 2400 and 4000. After that the edges of all specimens were polished by using diamond paste of 3 μm and finished with a diamond paste of 1 μm .

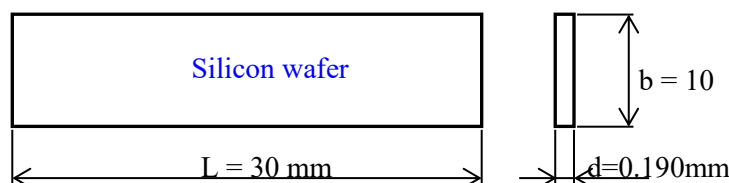


Figure 1. Dimension of silicon wafer specimen

2.2. Experimental procedure

The test set-up also was based on the ASTM C 1161 – 02c that used to measure of the ultimate strength of specified beam in bending at ambient temperature [8]. To ensure that design and

construction of the fixtures is such that a uniform force along the roller and specimen surface is produced, loading fixtures with an articulating as described in ASTM C 1161-02c test method. An articulating testing geometry were applied to reduces uneven force application caused by geometry variation of the test specimen or misalignment of the test fixtures by adjusting itself to the test specimen. In this research, 15 specimens were used for every testing condition for the purpose of calculating strengths in terms of mean and standard deviation values and of the Weibull parameters. The 4-point bending tests were done using an Instron Tensile Machine 5500 R, capacity 100 kN which operates with Bluehill 2 Material Testing Software. The strength of the multi crystalline silicon wafer specimens is calculated by using the standard formula for a rectangular beam in 4-point bending by using formulas read as follows:

$$\sigma = \frac{3PL}{4bd^2} \quad \text{and} \quad \varepsilon = 4.36 \frac{Dd}{L^2}$$

where : σ is maximum stress at outer fiber at a given force (MPa), P is force applied to the specimen (N), L is the outer support span (mm), b is the width of specimen (mm), d is the thickness of specimen and ε is the maximum strain at outer fibers at a given force.

3. Results and Discussion

3.1. Effect of screen printing mesh size on bending strength of mc-silicon solar cells

There are 2 types of screen-printing mesh sizes that were used, namely mesh 165 and mesh 325. The mesh size is defined as the number of threads in the mesh that cross per square inch. Both mesh sizes were applied in the metallization process with 3 types of metal paste: Ferro Al 101, Analog12 and DuPont PV 333. 3 types of mc-silicon solar cell specimens were defined as follow: 1). Silicon wafer + Al layer (Ferro Al 101, drying temperature 250 °C. 2). Silicon wafer + Al layer (Analog 12, drying temperature 250 °C); 3). Silicon wafer + Al layer (Dupont PV333, drying temperature 250 °C). As can be seen from figure 2, the screen printing mesh size affects the thickness of the aluminum layer. The thickness with mesh size 165 is approximately twice that with mesh size 325.

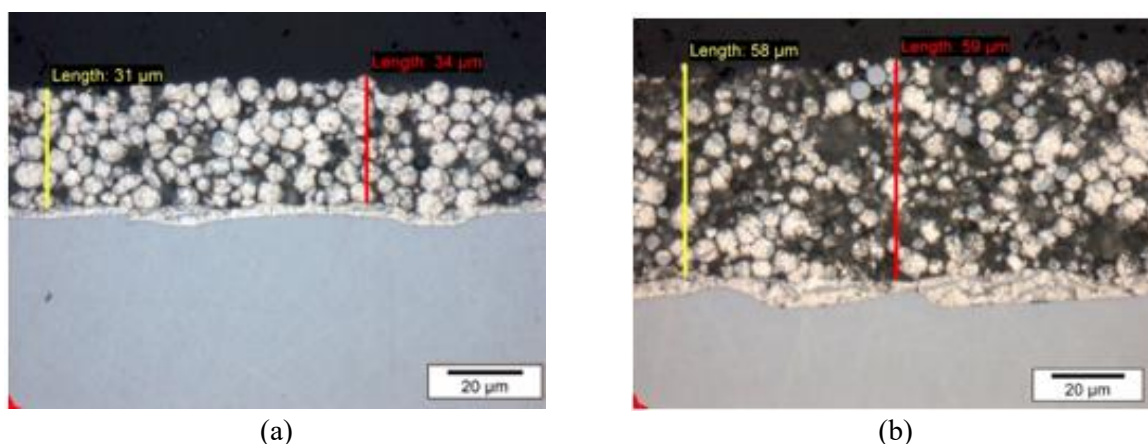


Figure 2. Microstructure of Al paste Ferro 101, (a) mesh size 325, (b) mesh size 165

A summary of the results of 4-point bending test is presented in figure 3. It could be concluded that the mesh size (i.e. 165 and 325) does not give an effect on the strength of the silicon wafer. Apparently, the strength of the silicon wafer is also not affected by the Al layer thickness. One would expect, however, that the thickness has a significant effect on the strength of the Al layer itself.

It could be reasoned that, since a thicker Al layer does not strengthen the silicon wafer, the strength mainly depends on the type of Al paste. The behaviour of interfaces, such as between the eutectic and the BSF layer and the eutectic and the Al bulk layer, might be very important for the strength of silicon wafers.

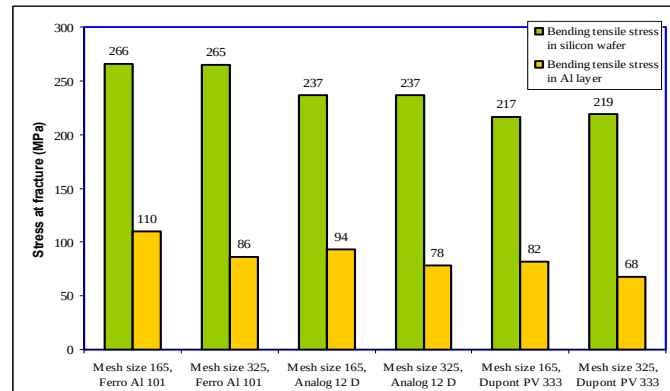


Figure 3. Correlation between the screen-printing mesh size on the bending tensile stresses (σ_0) at fracture of mc-silicon solar cell.

3.2. Effect of drying temperature on the bending strength of mc-silicon solar cells

Two different drying temperatures (250 °C and 350 °C) were chosen in order to investigate the influence of metal paste drying conditions on mechanical strength. 2 types of mc-silicon solar cells specimens are defined as: 1). Si + Al layer (Ferro Al 101, mesh 165) and 2). Si + Al layer (Ferro Al 101, mesh 165). The summary of 4-point bending test is presented in figures 4.

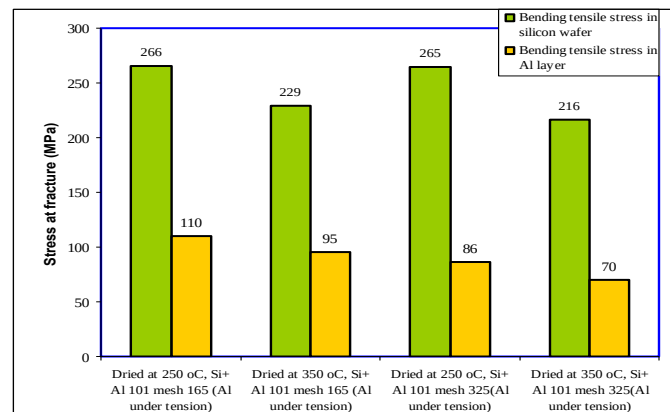


Figure 4. Influence of drying temperature of aluminium paste on the characteristic stresses (σ_0) at fracture of mc-silicon solar cells.

The drying temperature of aluminum paste has a significant effect on the bending tensile stress at fracture of mc-silicon solar cells. As can be seen in figure 3.3, specimens dried at low temperature (250 °C) have higher bending tensile stress at fracture than specimens dried at high temperature (350 °C). This tendency can be observed for both Al layer and silicon wafer.

Formation of the aluminum back contact layer contains many processing steps. The drying of aluminum paste is the 2nd step in order to drive-off organic solvent from the paste. After drying, a porous Al layer will cover the silicon wafer surface. This may lead to insufficient Al deposition, because the porous Al layer reduces the amount of Al available at the silicon surface. As a result, a non-uniform and thin Al-Si layer is formed, as the alloying process only starts locally on the silicon surface (figure 5). The aluminum paste layer needs special care during the drying process (a slow

heat-up ramp), because otherwise volatilizing solvent can build cavities in the paste. These cavities produce unalloyed regions and porosity, which are correlated with the location of the screen mesh openings of the screen printing process.

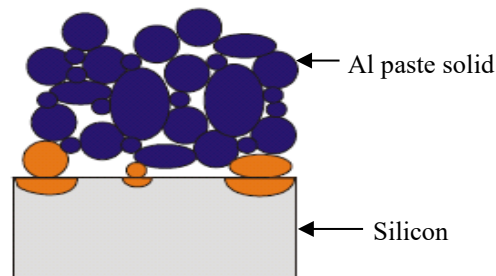
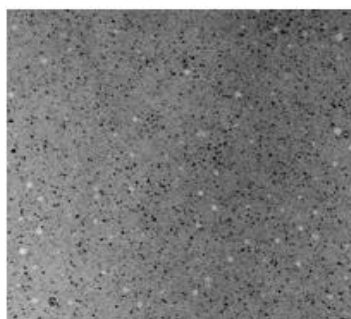
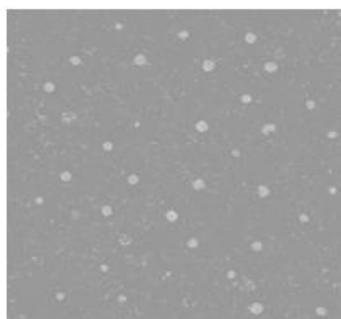


Figure 5. Melting of aluminium at $T = 660\text{ }^{\circ}\text{C}$ and start of the alloying process [4].



(a)



(b)

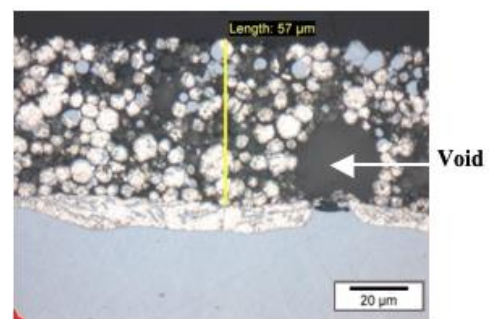


Figure 7

Figure 6. CT scan of a solar cell dried at (a) $250\text{ }^{\circ}\text{C}$, (b) $350\text{ }^{\circ}\text{C}$ and Figure 7. Big voids in the Al layer (Ferro 101 mesh size 165, dried at $250\text{ }^{\circ}\text{C}$)

3.3. Effect of metallization on mechanical strength of mc-silicon solar cells

Three types of cell metallization treated with similar testing conditions were compared. The mc-silicon wafer, i.e. without any metal layers, was used as a reference in order to find the influence of the metallization configuration on the mechanical strength. The effect of metallization on mechanical strength of mc-silicon solar cells is graphically presented in figure 8.

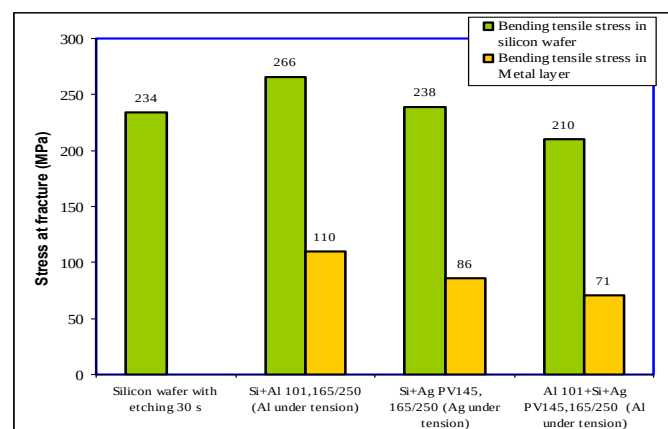


Figure 8. Influence of metallization pattern on the characteristic stresses (σ_0) at fracture of mc-silicon solar cells.

In this experimental step, 4 types of mc-silicon solar cells specimens were defined as follows:

- (a). Silicon wafer after etching 30 s (silicon wafer as a reference)
- (b). Si + Al 101 mesh 165, dried at 250 °C (silicon wafer covered by Al layer)
- (c). Si + Ag PV 145, mesh 165, dried at 250 °C (silicon wafer covered by Ag layer)
- (d). Al 101 + Si + Ag PV 145, mesh 165, dried at 250 °C (silicon wafer covered on both sides)

In general, different metallization configurations have different effects on the strength of the silicon wafer and metallization layers (Al layer and Ag layer). As can be seen, the presence of an Al layer increases the strength of silicon wafer, as compared to the reference. It might be that Al layer induces some plasticity at the outer fiber of silicon layer, thus providing a higher bending tensile stress at fracture.

The specimens fully covered by silver do not give any significant effect on the strength of the silicon wafer. It might be expected, that the dense microstructure of the bulk Ag layer, as presented in figure 9, can increase the strength of the silicon wafer compared to the reference. However, the internal stress induced by the thermal expansion coefficient mismatch between silicon wafer and silver layer during the metallization process might make the influence of the silver layer not so pronounced. The internal stress can be characterized by using curvature measurement by measuring the bow of specimen (silicon wafer + metal layer). It can suggest that the bowing can induce the compressive stress at the upper of neutral axis and tensile stress at the bottom one.

The situation is different for specimens that are covered on both sides. A cross section is presented in figure 10. The stress at fracture in the silicon wafer is below that of the reference specimen. This could mean this metallization configuration decreases the bending tensile stress at fracture of the silicon wafer. A possible explanation of this phenomenon is the presence of certain bowing that stresses the wafer, so if some further stress is applied, these stresses sum up and the specimen can fail at a lower applied force.

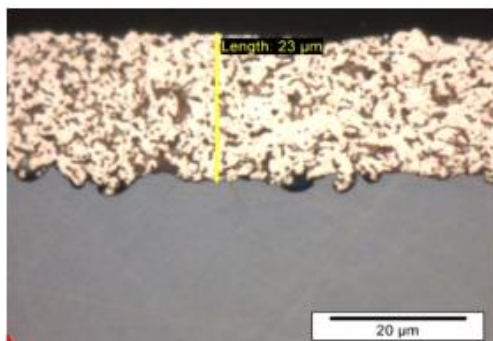


Figure 9. Microstructure of Ag PV 145 paste, mesh 165, dried at 250 °C.

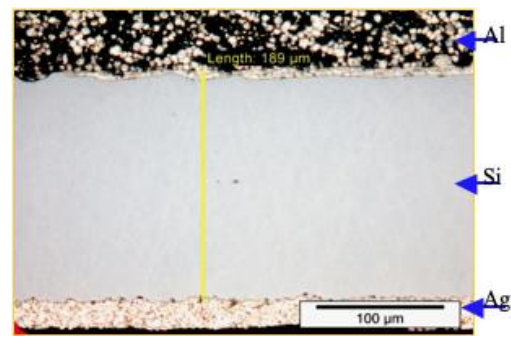


Figure 10. Cross section of Ag PV 145 + Silicon Wafer (Si) + Al 101, mesh 165, dried at 250 °C.

Due to metallization on both sides, the silicon wafer will be in compression; in which layer the early fracture cannot be defined (see figure 11). It could be that the Al layer, which is tested in tensile, contains higher residual stress level due to the presence of Al layer. It can suggest that the internal stresses induced from both sides of metal layer give a significant effect on mechanical stability of mc-silicon solar cells. But in this research the influence of internal stress (residual stress) due to CTE mismatch between metal layer and silicon wafer was not investigated, it should be investigated further.

Regarding to fracture surface, figure 11.a and 11.b give insight that delamination presence in the interface between Al layer and silicon wafer, no delamination can be found at the interface between the Ag layer and silicon wafer. The possible reason for these phenomena is the different behavior of contact formation of both layers in contact with silicon wafer. The eutectic layer that presence at the interface between Al layer and silicon wafer can serve as 2nd ductile phase that produce some plasticity

at this location to alter the mechanical behavior of silicon' outer fiber; on the other hand, no plasticity observed at the interface between Ag layer and silicon wafer Ag layer.

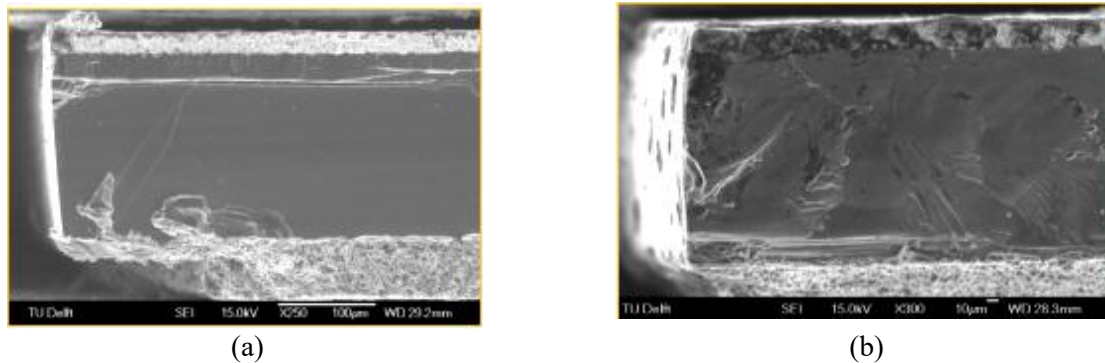


Figure 11. SEM image fracture surface of mc-silicon solar cell (Ag PV 145 layer + silicon wafer + Al 101 layer): (a) loading position Al layer under the tension, (b) tested with Ag layer surface under tension.

4. Conclusion

Screen printing mesh size produces the different thickness of metal layer (mesh 165 = 2 x mesh 325); but the mechanical strength of mc-silicon wafer is not affected by the Al layer thickness; it has a significant effect on the strength of the Al layer itself.

Dried of metal paste at low temperature (250 °C) is better for mechanical strength of mc-silicon solar cells as compared to dried at high temperature (350 °C); because the aluminum paste need a slow heat-up ramp during the drying process, otherwise volatilizing solvent can build cavities in the paste lead to porosity and reduce the amount of Al particle available at the silicon surface, resulting a non-uniform of the eutectic layer.

Metallization process can alter the mechanical strength of mc-silicon solar cell. It can be assuming that reducing of strength causing by presence of internal stress inside the specimen during metallization process.

The crack can initiate from the edges and surface defect and propagate along the preferred crystallographic plane. As a composite beam specimen, it cannot define in which layer (i.e. silicon wafer or metal layer) the earlier fracture will occur due to uncertainty of crack origin.

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