Breakage issues in silicon solar wafers and cells

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ABSTRACT

Reduction of silicon wafer thickness without increasing the wafer's strength can lead to a high fracture rate during subsequent handling and processing steps. The cracking of solar cells has become one of the major sources of solar module failure and rejection. Hence, it is important to evaluate the mechanical strength of silicon solar wafers and influencing factors. The purpose of this work is to understand the fracture behaviour of multicrystalline silicon wafers and to obtain information regarding the fracture of solar wafers and solar cells. The effects on silicon wafer strength of saw damage and of grain size, boundaries and triple junctions are investigated, while the effects of surface roughness and the damage layer removal process are also considered. Significant changes in fracture strength are found as a result of different silicon wafer crystallinity and surface roughness. Results indicate that fracture strength of a processed silicon wafer is mainly affected by the following factors: the saw-damage layer thickness, surface roughness, cracks/defects at the edges and the number of grain boundaries – which all serve as possible crack initiation points. The effects of metallization paste type and firing conditions on the strength of solar cells are also considered, with findings indicating that the aluminium paste type and firing conditions influence the strength of solar cells.

Introduction

An increase in silicon wafer size, combined with wafer thickness reduction without strengthening the wafer, leads to a high breakage rate during subsequent handling and processing, and results in high costs [1, 2]. It is well known that silicon is a brittle material that breaks easily during in-line processing due to stresses induced on the wafer surface and edges [3]. The cracking of silicon solar cells has become one of the major sources of solar module failure and rejection. Therefore, while it is important to investigate the electrical properties of silicon solar wafers and cells, the mechanical properties – especially the strength – also need to be carefully analyzed.

> "Cracking of silicon solar cells has become one of the major sources of solar module failure and rejection."

The purpose of this research is to determine the nature and source of defects (flaws) controlling the strength of multicrystalline silicon solar cells and to provide information regarding the strength of cells. In this paper several aspects regarding silicon wafer crystal structure, saw-damage removal, surface roughness parameters and metallization processing conditions are described in relation to mechanical strength. This strength is measured by a four-point bending method and results are statistically evaluated by a Weibull analysis, which provides information on the flaw distribution in the sample. The resulting data can be used to enhance production yields, improve cell reliability and establish mechanical criteria that ultimately lead to a reduction in cell costs.

Experimental conditions

Material preparation

Strength measurements were performed on rectangular multicrystalline (mc) silicon wafers and cells of 10 × 30mm^2 with a thickness of 200µm. Specific types of silicon crystallinity were chosen in order to investigate the effect of crystallinity features on the mechanical strength of the silicon wafer. All specimens were laser cut from a single cast block. In order to statistically evaluate the results, 15 neighboring specimens (thus featuring the same crystallinity features) were prepared.

The wafer specimens were divided into six groups according to crystallinity type (see Fig. 1), namely: one big grain, a triple junction, many small grains, a twin boundary, several grains and a grain boundary perpendicular to the loading direction. All the solar cell specimens were prepared using a standard industrial process.

In order to investigate the effect of saw-damage removal, specimens without a metal layer were etched for 30s in a HF(10%) + HNO_3(30%) + CH_3COOH(60%) solution. To investigate the effect of maximum firing temperature of the Al back-contact, six neighbouring wafers were processed under identical conditions, but with different peak temperatures; i.e., 750°C, 800°C, 850°C, 900°C and 950°C. Two different drying temperatures (250°C and 350°C) were also chosen in order to examine the influence on mechanical strength. In all these cases the same commercially available Al paste was used, a type which causes only a limited amount of cell bowing after firing. In addition, the influence of the aluminium paste composition on the strength of the cells was investigated for three different commercially available pastes (designated as paste A, B and C). Measurements of the amount of bowing that results from metallization were made by an optical method, using a Quick Vision Mitutoyo system over the full length of the solar cell (156mm).

The surface of the damaged layer in as-cut neighbouring samples was analyzed by Raman spectroscopy. This stress measurement technique was carried out at room temperature in the backscattering configuration using a Renishaw Raman spectrometer equipped with a He-Ne laser with an excitation wavelength of 633nm and a 100× objective. This resulted in a focused spot with a diameter of ~1µm and a penetration depth of a few µm.

Three types of specimens were prepared in order to analyze the effect of surface roughness. The surface conditions of these specimens included: the as-cut state (with saw-damage layer), a textured surface (an in-line process, used to remove the damaged layer and

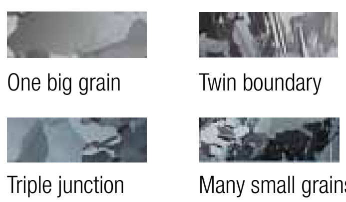

Figure 1. Four of the groups of specimens showing different crystallinity features.

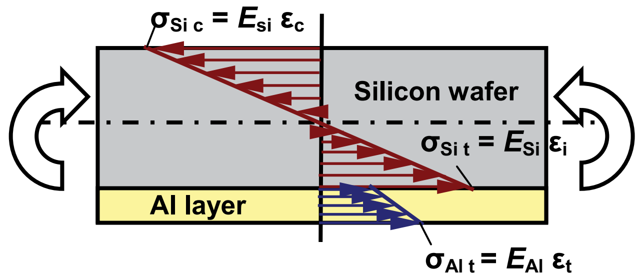

Figure 2. Stress distribution along the thickness of a silicon beam with an aluminium layer loaded in bending.

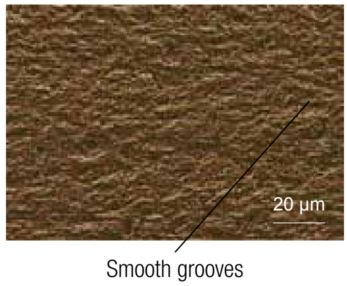

Figure 3. SEM micrograph of a typical surface of an as-sawn multicrystalline silicon wafer.

to create a highly textured silicon surface for trapping the light) and a chemically polished surface (15μm removal from both wafer surfaces).

It should be noted that the edges of all specimens were polished down to a 1μm finish and carefully examined with optical microscopy.

Strength measurement

The four-point bending test was chosen in this research because it results in a uniform bending moment across the specimen between the inner loading pins.

The test configuration, based on ASTM standard C 1161-02c [4], was used to measure the ultimate strength at ambient temperature [4]. The bending tests were performed using a 100kN Instron 5500R tensile machine equipped with a 10N load cell. The test fixture, designed especially for thin specimens, had a loading span equal to half the support span (i.e., a four-point – ¼ point configuration) and was semi-articulating. The crosshead speed was set such that the strain rate in the specimen was of the order of $10^{-4}\,s^{-1}$. From loading until fracture, the load and the deflection were monitored.

The stress, σ, and strain, ε, in the outer fiber of a specimen with a rectangular cross section loaded in four-point bending can be calculated as follows [5]:

$$\sigma = \frac{3PL}{4bd^2}, \quad \varepsilon = 4.36\frac{Dd}{L^2}, \qquad (1)$$

where P is the applied force, L the outer support span, b the specimen width, d the specimen thickness, D the deflection at the specimen centre. However, for solar cell specimens these standard formulae are not directly applicable. Specimens with an Al back-contact layer should be represented as a composite beam, consisting of two materials with different stiffnesses [6]. A linear strain distribution is assumed across the composite beam thickness. The stresses are then obtained by multiplying the strains by the modulus of elasticity for silicon (E_{Si}) and the aluminium metal layer (E_{Al}), respectively, leading to the stress distribution shown in Fig. 2.

The stress distribution is largely affected by the difference in elastic modulus of silicon and of the aluminium layer. In this work, the elastic modulus of the silicon was obtained from the wafer-bending tests and amounted to E_{Si} = 170GPa, averaged over the different crystallinity types. In our previous research [7], it was possible to calculate the overall elastic modulus of the Al contact layer using experimentally obtained bowing results and a bimetallic strip model. This amounted to an elastic modulus of around 43GPa, which is an average for the three different aluminium pastes investigated.

Results and discussion

Effect of saw-damage removal and silicon wafer surface roughness on mechanical strength

Silicon is a hard and brittle material and in order to cut Si ingots into thin wafers, a multi-wire sawing process is used, which can creates a highly stressed and damaged layer.

Fig. 3 shows an SEM micrograph of a typical surface of an as-sawn multicrystalline silicon wafer. As silicon is a brittle material, the smooth grooves on the surface cannot be explained by a melting and quenching of the surface leading to the formation of a thick silicon oxide layer. Therefore the samples were analyzed with a Raman spectrometer in order to check for phase transformations in the damaged layer.

The Raman spectrum, shown in Fig. 4, clearly indicates the presence of amorphous Si (a-Si) beside polycrystalline Si on the as-sawn surface. Measurements were made at many different positions of the wafer and in many locations an a-Si peak was visible, either big or small.

It is known that when indented or scratched at low load, silicon shows a phase transformation, rendering it ductile [8]. This results in a layer of amorphous silicon or – if the scratch is slow enough – a mixture of amorphous and metastable phases, which is similar to the phase transformation occurring during nanoindentation [9]. When the indenting (or scratching) tip is pressed on the silicon, it induces a high local pressure, transforming the brittle silicon into a ductile phase. On unloading, this ductile phase is not stable and transforms into a mixture of amorphous and metastable silicon phases [10]. In our study, amorphous silicon was

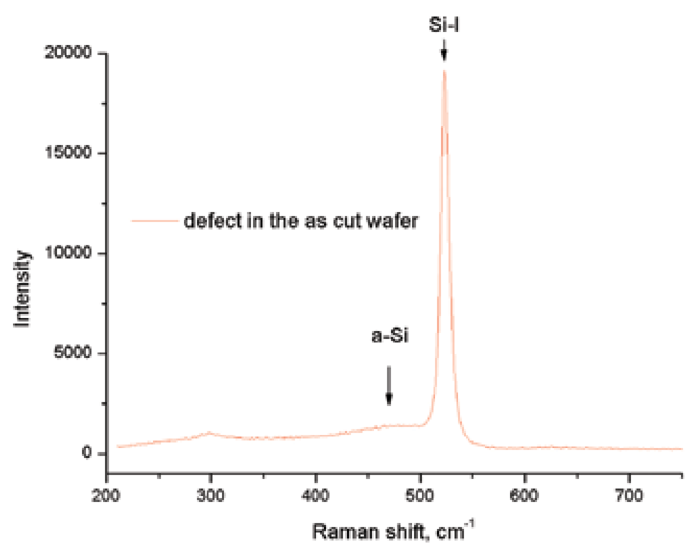

Figure 4. Representative Raman shift for the as-cut wafer, showing a local indentation-induced transformation of Si into a-Si.

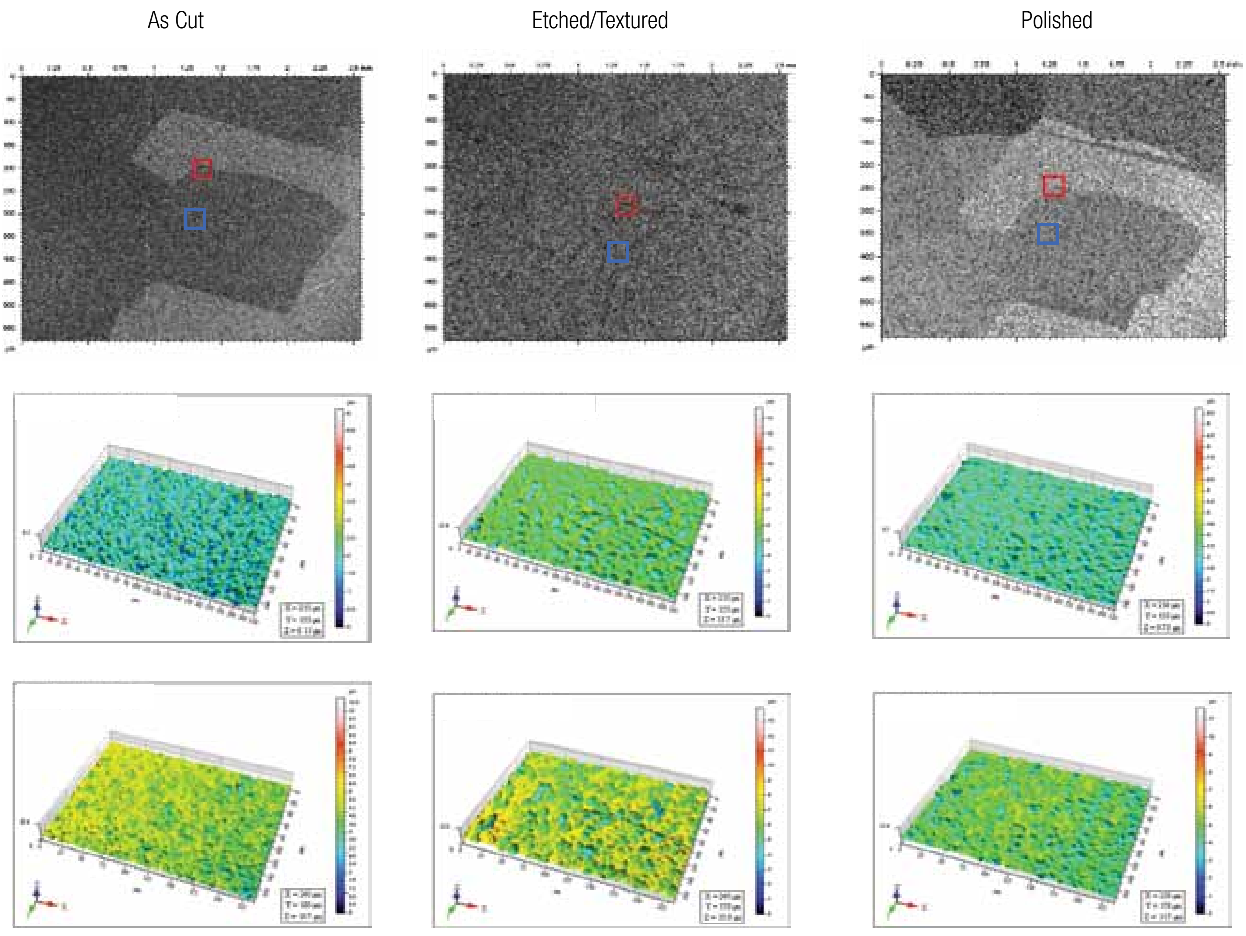

Figure 5. Representative surface roughness profiles for as-cut, textured and polished neighbouring wafers. Areas including the grain boundary are marked in red; areas in the grain are marked as blue.

found only in the smooth grooves (Fig. 3). The rough parts of as-sawn silicon wafers, where material is chipped off, mainly consist of stable crystalline silicon.

In order to view the influence of saw-damage etching (damage removal process) on the stress state and the mechanical strength of silicon wafers, two types of specimens were chosen: as-cut specimens and specimens etched by an acidic solution ($HF + HNO_3 + CH_3COOH$) for 30s.

In mc-silicon wafers, flaws and crack-like defects induced during processing cannot be avoided and it is known that wafer strength is directly related to the density, size and distribution of such microcracks. As can be seen in Table 1, the specimens without additional etching have a lower Weibull characteristic strength, σ_0, which is due to the presence of microcracks and a transformed amorphous silicon phase at the surface.

Etching conditions	σ_0 (MPa)	*m*(-)
No etching	155	9.4
With etching	234	8.3

Table 1. Effect of damage-layer removal on Weibull characteristic strength (σ_0) and modulus (*m*).

As a result of the etching process, the depth of surface microcracks is reduced; some cracks disappear completely; some crack tips become more blunted and the layer of transformed a-Si is removed. All of these effects reduce the risk of macrocrack initiation, making the material less susceptible to failure.

In this study, the wafer thicknesses are the same and the wafer edges are polished down to 1µm. Therefore these aspects will not affect the wafer strength and the surface roughness will determine the fracture strength of the multicrystalline silicon wafer. Fig. 5 shows representative confocal microscopy surface roughness profiles for sample with different surface conditions, i.e. as-cut, textured and polished down to 15µm, taken in the same areas of neighboring wafers.

As can be seen in Fig. 5, samples with a textured surface show a significant increase in surface roughness compared to the as-cut state. The roughness parameters *Sz* and *Sdr*, presented in Table 2, also indicate this; this most likely indicates the formation of etch pits.

It should be also noted that etching/texturing at the grain boundaries creates a much rougher surface, probably due to the preferential etching at the grain boundaries (see etched sample in Fig. 6a). The low value of the Weibull modulus (*m* < 8.5) (Table 2) shows that there is a large variation in the size of the largest defects, present at the tensile surface of tested textured silicon specimens.

Furthermore, despite the increase of surface roughness, there is still an improvement in mechanical strength of textured samples, probably due to the removal of the damaged layer.

"Further polishing of silicon wafers revealed a characteristic reduction in surface roughness."

In this research, the strength of the mc-silicon wafer increased by about 50% as a result of the etching/texturing (damaged layer removal) process. Thus, it can be suggested that the density of micro-cracks in the damaged layer is a more significant factor affecting mechanical strength of silicon wafers than surface roughness. Further polishing of silicon wafers revealed a characteristic reduction in surface roughness, as well as a significant increase in fracture strength (Table 2). A larger Weibull modulus, as

Silicon surface treatment	In the grain Sz, μm	Sdr, %	Grain boundary Sz, μm	Sdr, %	four-P bending strength, MPa	σ_0 (MPa)	*m* (-)
As-cut	5.70	14.6	6.11	12.2	78.0	160	9.4
Textured	12.7	28.2	13.7	45.8	90.0	240	8.3
Polished	9.73	10.8	10.6	10.0	117.5	285	10.1

Table 2. Effect of surface roughness on bending strength and Weibull characteristic strength, σ_0, and modulus, *m*, of multicrystalline silicon wafers. Here, *Sz* is the average difference between the five highest peaks and five lowest valleys; *Sdr* – the developed Interfacial area ratio, is expressed as the percentage of additional surface area contributed by the texture as compared to an ideal plane the size of the measurement region [11].

compared to the as-cut and textured state, indicates that polishing gives a much smoother silicon surface and a narrower defect distribution.

It can be concluded that in the absence of a damaged layer the fracture strength is inversely proportional to the surface roughness, i.e. $\sigma_0 \sim 1/R_a$, where σ_0 is the fracture strength and R_a is the surface roughness. It can also be concluded that as soon as the saw-damage layer is removed, the surface roughness profile is the second most detrimental factor affecting mechanical strength of silicon wafers.

Effect of mc-silicon wafer crystallinity on mechanical strength

Specific types of silicon wafer crystallinity were chosen for this research in order to investigate the effect on mechanical strength. All specimens were etched and polished in order to remove the damage induced by the sawing process. The four-point bending strength was analyzed using Equation 1. The results are given in Table 3, which lists the Weibull characteristic strength (σ_0) and the Weibull modulus (m) of 15 tests.

As can be seen from Table 3, it is possible to define three main characteristic groups based on the strength results. The specimens with one big grain in the middle have a much higher strength than those with many small grains in the middle. The four other crystallinity types, all having several grains in the middle, have an intermediate strength.

As for most brittle materials, the fracture strength of mc-silicon depends on both material-intrinsic properties, such as grain size, grain boundaries and crystal orientation, and on extrinsic variables such as flaws and microcracks [12]. The strength reduction due to the presence of many small grains might be related to the number of grain boundaries, which is proportional to the number of grains. Alternatively, the surface roughness might be different for varying crystallinity types, due to preferential etching of the grain boundaries; however, this effect can be excluded from this work, since polished samples were used. Furthermore, fracture patterns of the polished silicon samples subjected to four-point bending revealed a preferential propagation of the cracks near the grain boundaries.

Based on these results, it can be concluded that for polished mc-silicon wafers, crystallinity is the most significant factor affecting the strength, probably due to weak grain boundaries leading to intergranular fracture. Conversely, there is a mixed mode fracture for as-cut and for textured silicon wafers, where surface roughness and damaged layer are the most detrimental factors.

Crystallinity type	σ_0 (MPa)	*m* (-)
One big grain	293	8.5
Twin boundary	274	8.9
Triple junction	268	6.7
GB parallel to the loading direction	266	9.1
Several grains	260	7.4
Many grains	251	6.9

Table 3. Effect of crystallinity type of polished wafers on mechanical strength.

Effect of metallization paste type on mechanical strength of silicon solar cells

Three types of aluminium metal pastes were investigated in order to find the influence of the resulting metal layer microstructure on the mechanical strength of silicon solar cells. These specimens were treated as composite beams, consisting of two layers, i.e., a bulk mc-silicon wafer and an aluminium layer. The bending strength of the specimens was corrected using the appropriate flexural formulae [6]. Using these formulae, it was possible to determine the maximum tensile stress in each layer at the moment of specimen fracture. Unfortunately, the strength of the silicon wafer and the Al layer (i.e., the composite beam) cannot be determined individually in this research due to uncertainty concerning the layer from which the fracture originates.

As can be seen from Table 4, the type of aluminium metallization paste used has a significant effect on the strength when the specimens are loaded with the Al layer in tension. In this loading position, both of the specimen layers, i.e. the silicon wafer and the Al layer, are loaded in tension. Furthermore, due to its higher stiffness, the silicon wafer experiences the highest tensile stresses; unsurprisingly, for the reverse loading position the effect of paste type on the mechanical strength is not so significant.

The maximum tensile stress in a silicon solar cell loaded with the Al layer under tension will be located at the interface between the silicon wafer and the aluminium layer. In order to understand the effects on the solar cell's strength, it is important to consider the microstructure of the layers present locally.

From previous investigations [7], it was found that the Al layer consists of a eutectic layer with a porous layer on top. The eutectic layer is a uniform Al-Si bulk alloy, being in full contact with the BSF layer, and as a result with the silicon wafer. The porous layer has a composite-like microstructure consisting of three main components: 1) spherical hypereutectic Al-Si particles, 2) bismuth-silicon glass and 3) porosity. It was shown that the porous layer is not uniform and does not fully cover the eutectic layer.

All specimens with an Al layer show an increase in bending strength (as compared to the reference etched silicon wafer specimens), probably due to the formation of the eutectic layer (~12% Si). Since silicon is a very brittle material that only exhibits elastic behaviour, the presence of a second ductile phase (i.e., the eutectic layer) could induce some plasticity at the outer fiber, thus altering the stress distribution and affecting possible crack initiation. This ductile phase (eutectic layer) can serve as a bridge for possible critical microcracks, thereby improving the strength of mc-silicon solar cells.

The different effects of Al pastes on the mechanical strength of mc-silicon solar cells can be explained by the differences in layer microstructure. There are a number of features that might affect the mechanical strength, such as the eutectic layer and its thickness, the total Al layer thickness (which results from the Al particle size and its distribution) and the amount of porosity and the bismuth glass fraction.

Al paste type	Al suface in tension			Si surface in tension		
	Stress at fracture in Al (MPa)	Stress at fracture in Si (MPa)	Weibull modulus, *m* (-)	Stress at fracture in Al (MPa)	Stress at fracture in Si (MPa)	Weibull modulus, *m* (-)
A	110	266	6.3	71	206	7.8
B	94	237	6.5	68	195	8.5
C	82	217	4.8	67	193	9.6

Table 4. Effect of aluminium paste type on the characteristic stress at fracture in silicon solar cells.

Drying temperature (°C)	Characteristic stress at fracture (Al under tension)		Weibull modulus m (-)
	σ_{Si} (MPa)	σ_{Al} (MPa)	
250	266	110	6.3
350	220	90	6.8

Table 5. Effect of aluminium paste drying temperature on the characteristic stresses at fracture in silicon solar cells.

Firing temperature (°C)	Characteristic stresses at fracture (Al under tension)		Bowing of a complete cell (mm)
	σ_{Si} (MPa)	σ_{A1} (MPa)	
750	149	59	0.48
800	171	68	1.16
850	187	73	1.40
900	193	77	1.43
950	203	80	1.80

Table 6. Effect of maximum firing temperature on the characteristic stresses at fracture and amount of bowing of silicon solar cells.

Effect of aluminium paste drying and firing temperatures on mechanical strength of silicon solar cells

Two different Al paste drying temperatures (250°C and 350°C) were chosen in order to investigate the influence on mechanical strength. As can be seen from Table 5, the paste drying temperature has an effect on the bending tensile stresses in mc-silicon solar cells at fracture. Specimens dried at low temperature (250°C) show higher characteristic stresses at fracture than specimens dried at high temperature (350°C).

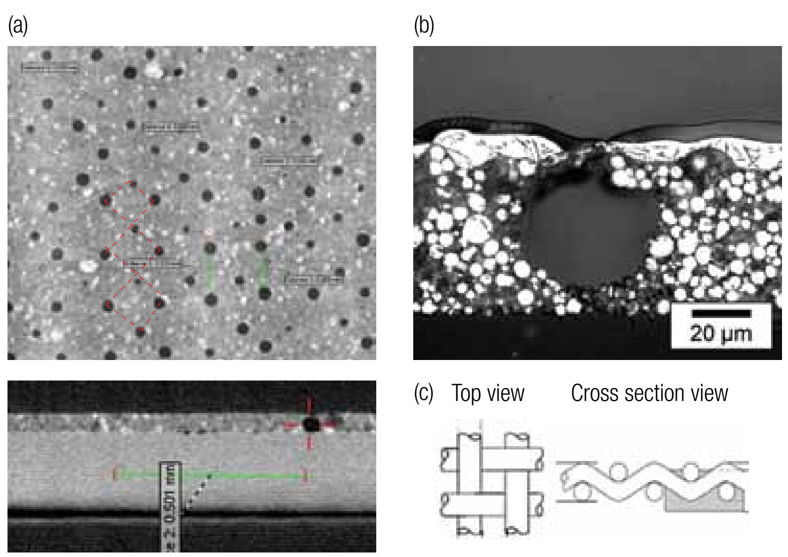

Figure 6. a) Volumetric representation (top image) of a solar cell cross-section and a 2D X-ray (bottom image) of the Al layer, showing defects induced by the screen-printing process (black part: voids; white: bismuth; grey: Al and Si). The dashed red line represents a reconstructed screen-printing mesh. b) Optical image of the solar cell cross-section showing a process-induced cavity. c) Schematic of an industrial screen-printing mesh, used for the application of metallic pastes.

In previous investigations [13], a computed tomography (CT) study of the Al back-contact layer revealed the presence of spherical voids inside the porous Al layer. It was shown that these voids have a homogenous and systematic distribution across the entire Al layer, and were caused by the screen-printing process (Fig. 6). It was found that there is a significant change in the defect concentration between the samples processed at different drying temperatures; i.e., drying at 350°C creates relatively large holes (10 to 20µm^2) in a well-defined pattern, resulting in a more porous layer.

Drying at 250°C gives smaller holes and a denser Al layer structure. The presence of voids in the aluminium layer, produced by the screen printing process, creates a non-uniform stress field at the interfaces, thus affecting the strength. Hence, drying aluminium paste at lower temperature (250ºC) can be advised as the most optimal condition from a mechanical stability point of view.

The other effect that has been investigated in the course of this study is the relationship between the maximum firing temperature of the aluminium layer and the fracture strength of the silicon solar cell. For this purpose, six neighbouring wafers were processed with the same conditions, but with different peak temperatures; i.e., 750–950°C (Table 6).

Table 6 shows the effect of the maximum firing temperature on the characteristic stresses at fracture in the Al and Si layers. As can be seen, there is a strong correlation between the maximum firing temperature and the stresses at fracture; the higher the firing temperature, the higher the characteristic stresses. Furthermore, it should be noted that increasing the firing temperature increases the amount of bowing of the complete cell, as shown in Table 6.

These effects can be explained by the increased eutectic layer thickness with peak firing temperature. As can be understood from the Al-Si phase diagram [14], increasing the firing temperature leads to an increased amount of Si dissolution and an increased amount of liquid phase, resulting in a thicker eutectic layer.

Thus, both the thickness of the eutectic layer as well as uniformity (fewer defects) of the aluminium back-contact layer can be considered as important parameters controlling mechanical stability of silicon solar cells.

Conclusions

Breakage issues and mechanical strength of mc-silicon wafers and solar cells were investigated using a combination of four point bending test, bowing measurements, confocal microscopy, Raman spectroscopy and X-ray computed tomography. The study yields the following information:

- Multicrystalline silicon wafer crystallinity has a significant effect on the mechanical strength.
- Surface and edge defects, such as microcracks, grain boundaries and surface roughness, are the most probable sources of mechanical strength degradation. Reduction of potential microcracks leads to an increase of the fracture strength of an mc-silicon wafer.
- There is a relationship between aluminium paste composition, mechanical strength of a cell and amount of cell bowing.
- When loaded in tension, the aluminium layer improves the strength of a solar cell. The eutectic layer within this structure probably shows some plasticity and can also serve as a bridge for possible critical microcracks at the silicon wafer surface.
- Drying aluminium paste at low temperature (250°C) yields a better mechanical strength of mc-silicon solar cells than drying at a higher temperature (350°C).
- There is a strong correlation between maximum firing temperature, bowing and fracture strength of solar cells; the higher the firing temperature the higher the fracture strength and the greater the bowing.
- Thickness of the eutectic layer as well as uniformity (fewer defects) of the aluminium back-contact layer can be considered as important parameters controlling mechanical stability of silicon solar cells.

References

[1] Brun, X.F & Melkote, S.N. 2009, "Analysis of stresses and breakage of crystalline silicon wafers during handling and transport", *Sol. Energy Mater. Sol. Cells,* Vol. 93, pp. 1238–1247.

[2] Wang, P.A. 2006, "Industrial challenges for thin wafer manufacturing" in *Proc. 4th WC PVEC*, Waikoloa, Hawaii, USA, pp. 1179–1182.

[3] Lawn, B.R. 1993, *Fracture of Brittle Solids*, Cambrige University Press, Cambrige, UK.

[4] ASTM Standard C 1161-02c, 2008, *Standard Test Method for Flexural Strength of Advanced Ceramics at Ambient Temperature*, ASTM International, West Conshohocken, Pennsylvania, USA.

[5] ASTM Standard C 1341-06, 2006, *Standard Test Method for Flexural Properties of Continuous Fiber-reinforced Advanced Ceramic Composites*, ASTM International, West Conshohocken, Pennsylvania, USA.

[6] Gere, J.M. & Goodno, B.J. 2009, *Mechanics of Materials,* Seventh ed., Cengange Learning, USA.

[7] Popovich, V.A. et al. 2010, "Microstructure and mechanical properties of aluminium back-contact layers", *Sol. Energy Mater. Sol. Cells,* Vol 95, No 1.

[8] Gassilloud, R. et al. 2005, *Phys. Stat. Sol.* (a) Vol. 202, No. 15, pp. 2858–2869.

[9] Kailer, A. et al. 1997, *Appl. Phys,* Vol. 81, No. 7, pp. 3057–3063.

[10] Jang, J. et al. 2005, *Acta Materialia,* Vol. 53, pp.1759 – 1770.

[11] Roughness Parameters [available online at http://www.imagemet.com/WebHelp/spip.htm#roughness_parameters.htm].

[12] Cook, R.F. 2006, "Strength and sharp contact fracture of silicon", *J. Mater. Sci.*, Vol. 41.

[13] Popovich, V.A. et al. 2010, "Application of x-ray computed tomography in silicon solar cells", *Proc. 35th PVSC*, Honolulu, Hawaii, USA.

[14] a/u MATTER [available online at http://aluminium.matter.org.uk].

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