

MECHANICAL STRENGTH OF MULTICRYSTALLINE SILICON SOLAR CELLS AND INFLUENCING FACTORS

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ABSTRACT

Silicon wafer thickness reduction without increasing the wafer strength leads to a high fracture rate during subsequent handling and processing steps. 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 solar cells and factors influencing this. The purpose of this work is to understand the fracture behavior of silicon solar cells and to provide information regarding the bending strength of the cells.

The effects on silicon wafer strength of saw damage and of triple junctions, grain size and grain boundaries are investigated. Also the effects of metallization paste type and firing conditions on the strength of solar cells are considered. Significant changes in fracture strength are found as a result of silicon wafer crystallinity and of metallization morphology. It is observed that the aluminum paste type influences the strength of the solar cells.

1. INTRODUCTION

Silicon wafer thickness reduction without increasing the wafer strength leads to a high fracture rate during subsequent handling and processing steps. Cracking of solar cells has become one of the major sources of solar module failure and rejection. Therefore, it is not only important to investigate the electrical properties of silicon solar cells, but also the mechanical properties, especially the strength. Factors influencing strength and the mechanism of fracture have to be understood in order to minimize the fracture rate and to optimize the processing steps.

In this work the fracture 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 purpose of this research is to determine the nature and source of the defects (flaws) controlling the fracture of silicon solar

cells and to provide information regarding the bending strength of the 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 paper several aspects regarding silicon wafer crystal structure and solar cell processing conditions, including saw damage removal and metallization, are described in relation to mechanical strength.

2. EXPERIMENTAL CONDITIONS

2.1. Material preparation

Strength measurements were performed on rectangular multicrystalline (mc) silicon wafers and cells of 10 x 30 mm² with a thickness of 200 μ m. 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 one 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 6 groups according to crystallinity type, see Fig. 1, namely:

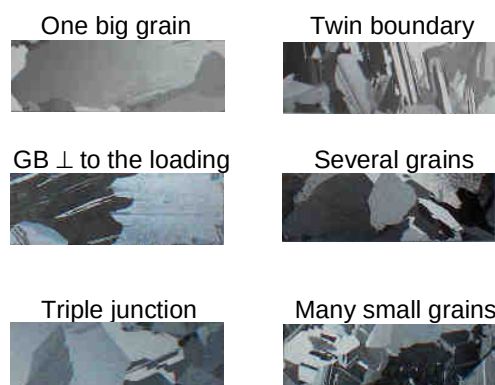


Figure 1. Groups of specimens showing different crystallinity features.

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 30 s in a HF(10%) + HNO₃(30%) + CH₃COOH(60%) solution. To investigate the effect of maximum firing temperature of the Al back contact, six neighboring wafers were processed with 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 chosen in order to find its influence on mechanical strength. In all cases the same commercially available Al paste (designated as paste A, B and C) was used, a type which only causes a limited amount of cell bowing after firing. However, in order to examine the influence of the aluminium paste composition on the strength of the cells, three different commercially available pastes were investigated (pastes designated as 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 (156 mm).

The effects of surface roughness and saw damage were analyzed by comparing results from as-cut wafers with those from chemically etched specimens. In both cases only neighboring wafers were used. Confocal microscopy was used to evaluate surface roughness profiles.

The edges of all specimens were polished down to a 1 µm finish.

2.2. 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; hence, the specimen will fracture at a point where the largest surface or edge defect is present.

The test configuration, based on ASTM standard C 1161-02c [1], was used to measure the ultimate strength of a beam in bending at ambient temperature [1]. The bending tests were performed using a 100 kN Instron 5500R tensile machine equipped with a 10 N 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. During loading, the load and the deflection were monitored until specimen fracture.

The outer fiber stresses and strains in the silicon wafer specimens are calculated by using the formulas for a rectangular beam loaded in the 4-point bending configuration used [2]:

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

where σ = maximum stress in the outer fiber at a given force (MPa), ϵ = maximum strain in the outer fiber, P = applied force (N), L = outer support span (mm), b = width of the specimen (mm), d = thickness of the specimen (mm), D = deflection at the center of the beam (mm).

However, for solar cells specimens the standard formulas are not applicable, because these specimens should be represented as composite beams, consisting of two materials with different stiffnesses, *i.e.* silicon and the Al back contact layer [3]. A linear strain distribution is assumed across the composite beam thickness. The stresses are obtained by multiplying the strains by the modulus of elasticity for silicon (E_{Si}) and the aluminum metal layer (E_{Al}), respectively, leading to the stress distribution shown in Figure 2.

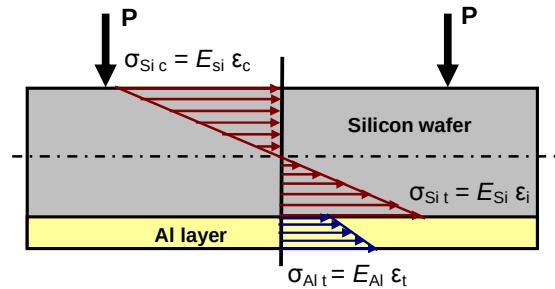


Figure 2. Distribution of stress (σ) in a silicon beam with an aluminum layer loaded in bending.

The stress distribution is largely affected by the difference in elastic modulus of silicon and of the aluminum layer. In this work the elastic modulus of the silicon was obtained from the wafer bending tests and amounted to $E_{Si} = 170$ GPa, averaged over the different crystallinity types. The elastic modulus of the Al layer is largely affected by particle size, glass frit fraction and firing conditions, and can be expected to be lower than the elastic modulus of bulk Al. In our previous research [4], 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 43 GPa, which is an average for the three different aluminum pastes investigated.

3. RESULTS AND DISCUSSION

3.1. Effect of saw-damage removal

In order to see the influence of saw damage etching on the mechanical strength of silicon wafers, 2 types of specimens were chosen: the as-cut specimens and specimens etched by an acidic solution ($\text{HF} + \text{HNO}_3 + \text{CH}_3\text{COOH}$) for 30 s. 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 microcracks [2, 5]. As can be seen in Table 1, the specimens without any additional etching have a lower Weibull characteristic strength, σ_0 , which is presumably due to the presence of microcracks at the surface loaded in tension.

Table 1. Effect of saw-damage etching on Weibull characteristic strength (σ_0).

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

If the density of microcracks is high, the probability that a macrocrack initiates and propagates for a given stress is also high, which explains the lower strength in specimens without any additional etching treatment. Microcracks are induced during the sawing process while slicing the wafers from the ingot. As a result of etching, the depth of surface microcracks is reduced, some cracks disappear complete and some crack tips become more blunted. Both of these effects reduce the risk of macrocrack initiation, making the material less susceptible to failure.

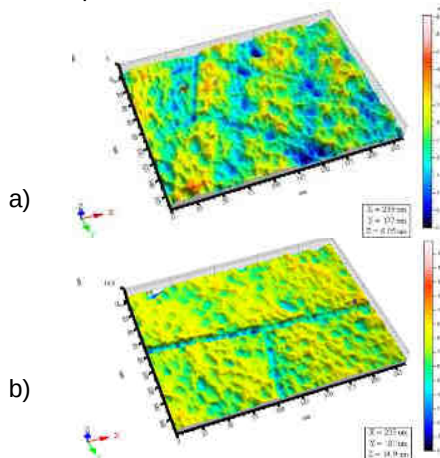


Figure 3. Representative surface roughness profiles: a) one big grain, b) triple junction and c) surface roughness parameters, where S_z is an average difference between the 5 highest peaks and 5 lowest valleys; S_{dr} - the Developed Interfacial Area Ratio, which is expressed as the percentage of additional surface area contributed by the texture as compared to an ideal plane the size of the measurement region.

In this research, the strength of the mc-silicon wafer was increased by about 50% as a result of the etching process.

3.2. 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 by an acidic solution for 30 s to remove the damaged layer induced by the sawing process. The four-point bending strength was analyzed by Eq. (1). The results are given in Table 2, which lists the Weibull characteristic strength (σ_0) and the Weibull modulus (m) of 15 tests.

As can be seen from Table 2, 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.

Table 2. Effect of crystallinity type on wafer strength.

Crystallinity type	σ_0 (MPa)	m (-)
One big grain	287	7.9
Twin boundary	256	8.6
Triple junction	255	5.9
GB parallel to the loading direction	241	8.4
Several grains	228	5.5
Many grains	208	5.7

Crystallinity type	S_z (μm)	S_{dr} (%)	Average fracture force (N)
One big grain	7.5	5	5.5 ± 0.8
Many small grains	11	27	3.6 ± 0.7
Triple junction	13	25	4.8 ± 0.8

Table 3. Effect of aluminum paste type on the characteristic stress at fracture in silicon solar cells.

Al paste type	Al surface in tension			Si surface in tension		
	Maximum tensile stress in Al (MPa)	Maximum tensile stress in Si (MPa)	Weibull modulus (-)	Maximum tensile stress in Al (MPa)	Maximum tensile stress in Si (MPa)	Weibull modulus (-)
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

As for most brittle materials, the fracture strength of an mc-silicon wafer depends on both material-intrinsic properties, such as grain size, grain boundaries and crystal orientation, and on extrinsic variables such as flaws and microcracks [6]. 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 different crystallinity types, due to preferential etching of the grain boundaries. Surface roughness parameters of the three main crystallinity groups are given in Figure 3. As can be seen, there seems to be some correlation between surface roughness and the fracture strength: the higher the surface profile, the lower the fracture strength force, see Figure 3c.

However, at this stage of research it is difficult to say which effect on the mechanical strength, extrinsic or intrinsic, is the most significant.

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

Three types of aluminum metal pastes were investigated in order to find the influence of the microstructure resulting from firing on the mechanical strength of silicon solar cells. It should be noted, that these specimens were treated as composite beams, consisting of two layers, *i.e.* a bulk mc-silicon wafer and an aluminum layer. The bending strength of the specimens was corrected using the appropriate flexural formulas [3]. Using these formulas, 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 in which layer the fracture originates.

As can be seen from Table 3, the type of aluminum metallization paste has a significant effect on the strength when the specimens are loaded with the Al layer in tension. In this load-

ing 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. On the other hand, for the reverse loading position the effect on the mechanical strength is not so significant.

It should be noted that specimens with an Al layer show an increase in bending strength (as compared to the reference silicon wafer specimens – etched silicon wafers), possibly due to the formation of a eutectic layer (~12% Si) and a BSF layer ($1-2 \times 10^{18}$ atom Al/cm³ Si).

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 aluminum layer. In order to understand 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 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 found, that the Al layer is not uniform and does not fully cover the eutectic layer. The eutectic layer, however, represent a uniform Al-Si bulk alloy, being in full contact with the BSF layer, and as a result with the silicon wafer.

The eutectic layer is expected to have a significant effect on the mechanical behavior of the silicon wafer at the outer fiber. Since silicon is a very brittle material that only exhibits elastic behavior, the presence of a 2nd 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. Furthermore, this ductile phase (eutectic layer) can serve as a bridge for possible critical microcracks, thus 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 microstructures. There are a number of microstruc-

tural features that might affect the mechanical strength, such as the total Al layer thickness, the amount of porosity, the bismuth glass fraction and the thickness of the eutectic layer. The microstructures of the aluminum pastes were studied previously [7].

In general, three main parameters affect the mechanical strength of mc-silicon solar cells with an aluminum contact layer, namely the eutectic layer, the Al layer thickness (which results from the Al particle size and its distribution), and the amount of porosity and the bismuth glass fraction.

3.4. Effect of aluminum 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 bending characteristic stresses at fracture than specimens dried at high temperature (350 °C).

Table 5. Effect of aluminum paste drying temperature on the characteristic stresses at fracture and max. force in silicon solar cells.

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

In previous investigations [7], a computed tomography (CT) study of the Al back contact layer revealed the presence of spherical voids inside the porous bulk Al layer. It was shown that these voids have a homogenous and systematic distribution across the entire Al layer, and were caused by screen printing process-induced defects. 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 ($10\div 20 \mu m^2$) 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 aluminum layer, produced by the screen printing process, creates a non-uniform stress field at the interfaces, thus affects the strength. Hence, drying aluminum paste at lower temperature (250 °C) can be advised as the most optimal condition from a mechanical stability point of view.

The other effect that was investigated in the course of this study is the relationship between the maximum firing temperature of the aluminum back contact layer and the fracture strength of the silicon solar cell. For this purpose, six neighboring wafers were processed with the same conditions, but with different peak temperatures, *i.e.* 750 °C, 800 °C, 850 °C, 900 °C and 950 °C.

Table 6 shows the effect of the maximum firing temperature on the characteristic stresses at fracture in silicon solar cells. As can be seen, there is a strong correlation between the maximum firing temperature and the stresses at fracture, *i.e.* the higher the firing temperature the higher the characteristic stresses at fracture in the Al and Si layers. 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 it is expected from the Al-Si phase diagram [8], increasing the firing temperature leads to an increased amount of Si dissolution and increased amount of liquid phase, which will result in a thicker eutectic layer.

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

Table 6. Effect of maximum firing temperature on the characteristic stresses at fracture, max. fracture force and maximum bow in silicon solar cells

Firing temperature (°C)	Max. fracture force (N)	Characteristic stresses at fracture (Al under tension)		Bowing of complete cell (mm)
		σ_{Si} (MPa)	σ_{Al} (MPa)	
750	3.9 ± 0.3	149 ± 11.5	59 ± 4.6	0.48
800	4.5 ± 0.4	171 ± 16.1	68 ± 6.3	1.16
850	5.0 ± 0.3	187 ± 20.3	73 ± 7.6	1.40
900	5.1 ± 0.5	193 ± 22.5	77 ± 8.9	1.43
950	5.3 ± 0.5	203 ± 18.0	80 ± 7.2	1.80

CONCLUSIONS

The mechanical strength of multicrystalline (mc) silicon solar wafers and solar cells was investigated using a four-point bending test. The characteristic strength of the wafers and the characteristic stresses at fracture in the Si and Al cell layers were calculated. The study showed that:

- Mc-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 a mc-silicon wafer;
- There is a relation between aluminum 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 layer probably shows some plasticity and can also serve as a bridge for possible critical microcracks at the silicon wafer surface;
- Drying aluminum paste at low temperature (250 °C) yields a better mechanical strength of mc-silicon solar cells than drying at higher temperature (350 °C);
- There is a strong correlation between maximum firing temperature, bowing and fracture strength of solar cell, *i.e.* the higher the firing temperature the higher the fracture strength and the higher the bowing.

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