

## MECHANICAL AND ELECTRICAL CHARACTERISATION OF THIN MULTI-CRYSTALLINE SILICON SOLAR CELLS

A. Schneider, E. Rueland, A. Kraenzl, P. Fath

University of Konstanz, Department of Physics, P.O.Box X916, D-78457 Konstanz, Germany

Author for correspondence: A.Schneider@uni-konstanz.de, Tel.: +49-7531882082, Fax: +49-7531883895

**ABSTRACT:** One of the key issues for future industrial solar cell production is the use of wafers with reduced thickness and enlarged area. The current standard thickness for industrial solar cells is between 260  $\mu\text{m}$  and 330  $\mu\text{m}$  and there is a general trend towards 200  $\mu\text{m}$  thick wafers. Mechanical wafer stability strongly decreases with wafer thickness, ranging in a Twist-Test from 9.2 Newton for 330  $\mu\text{m}$  thickness down to 1.9 Newton for 150  $\mu\text{m}$ . To compare the stability of as-cut material with surface treated wafers, the mechanical stability after alkaline etching and isotropic texturing was determined for wafers of different thicknesses. Wafer material thickness has a strong influence on solar cell parameters. Our measurements show a drop in efficiency of almost 1% for 150  $\mu\text{m}$  thick wafers when compared with 330  $\mu\text{m}$  thick wafers. With the bending measurement, a slope could be calculated from the data that predicts the fracture force in a very early measurement state. To guarantee that the wafer material is not damaged by the stability measurement, cycling tests with different mc-wafers were performed. The results on four different materials showed no influence of the measurement method on the mechanical stability.

**Keywords:** Mechanical Stability - 1, Multi-Crystalline - 2, Texturisation - 3

### 1 INTRODUCTION

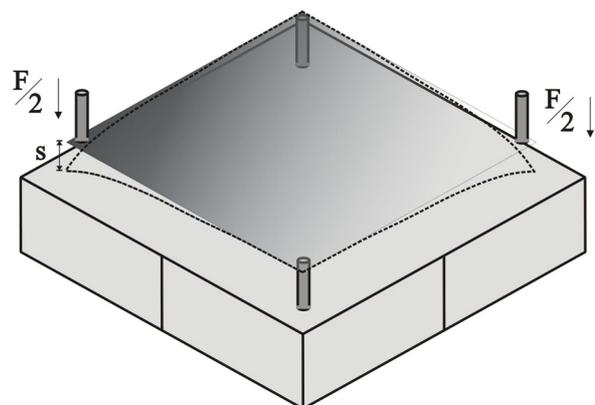
The main aim of this work was to investigate the influence of wafer thickness on cell performance and mechanical stability. With a specially developed stability tester, called a Twist-Tester, the fracture force required to break wafer material could be examined in a four point bending test. Neighbouring wafers of different thicknesses, ranging from 140-330  $\mu\text{m}$  were used to study the mechanical stability in the as-cut state, after alkaline etching and after isotropic texturing. The calculated slope of the stress/strain data was used to predict the fracture force before wafer breakage. Cycling tests with several different mc-wafers were performed to guarantee that the stability measurement had no harmful effect on the material. Furthermore, cells of different thicknesses were produced using a standard industrial solar cell process to investigate the effect of thickness variation on solar cell parameters.

### 2 MECHANICAL STABILITY MEASUREMENTS

The change in mechanical behaviour of silicon wafers with decreasing thickness is twofold. Firstly, the fracture force is strongly decreasing due to the larger impact of surface defects. Even with very little saw damage, a certain amount of surface cracks are still found in the material. For thinner wafer material, the total stability is therefore lower because crack growth is faster with less inner resistance. Secondly, the thinner the wafer the higher the flexibility of the material.

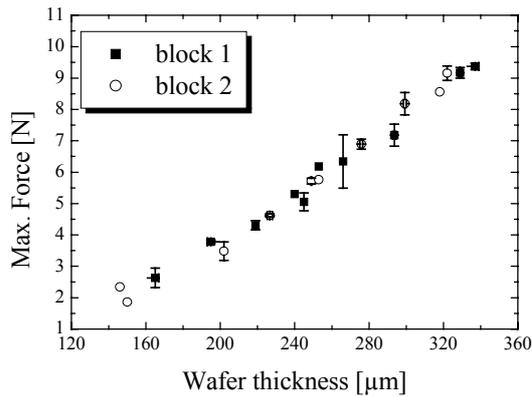
One could argue that this stronger flexibility would lead to a higher mechanical yield in production lines by allowing larger wafer deflections. This statement is true for handling actions between process steps, in which the material is strained, but existing cracks would lead to very early breakage even if the flexibility is high. This is mainly the case for mechanically demanding process steps, such as thermal diffusion [1]. To investigate the wafer stability, a special measuring setup was developed, known as the Twist-Tester [2]. The wafer lies on two fixed dowel pins, which support two diagonally opposing corners of the wafer. The measurement forces are applied

by downward movement of two pins pushing on the remaining two corners of the wafer (figure 1). First suggested by Chen [3], this measurement setup offers the possibility to stress the entire wafer and is therefore sensitive to both flaws in edge regions and in the internal wafer area.



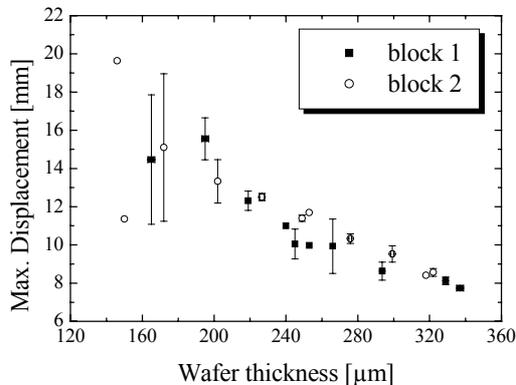
**Figure 1:** Four-point twisting of a wafer. The wafer is held by two dowel pins while it is stressed by downward bending of the two unsupported corners.

In a first experiment, we investigated the effect of thickness variation on fracture force on neighbouring wafers. Former work showed the strong influence of wafer thickness on mechanical stability for mono-crystalline wafers [4], whereas this work was concerned with multi-crystalline material. We used 10x10  $\text{cm}^2$  wafers for this experiment. Figure 2 shows the large stability decrease for thinner material. From these experiments we found that the 140  $\mu\text{m}$  thick wafers had only 20% of the stability, of the standard 330  $\mu\text{m}$  thick wafers. An increase in flexibility was observed, as shown in figure 3. Presented is the average value of 4-10 wafers for two different blocks from the same ingot. The impact of these experiments on solar cell production would lie in a much lower mechanical yield and therefore emphasises the importance of crack detection.



**Figure 2:** Fracture force measured with the Twist-Tester for wafers with varying thicknesses. Neighbouring wafers of two different blocks were used for these experiments.

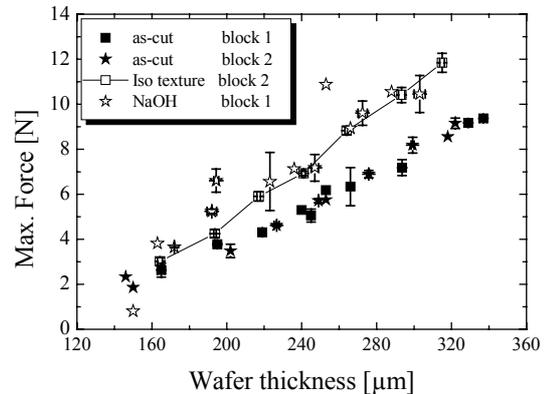
Former experiments showed a strong increase in fracture force for as-cut wafer material after alkaline etching [4]. This benefit was a result of the removed saw damage with a stability increase of 9% compared to the as-cut wafer. Etching time and wafer material have a strong influence on this effect. To investigate this effect for wafers of different thicknesses and compare it to the as-cut material, further stability measurements were performed. The wafer material was etched for 6 minutes in an 80°C NaOH-etch. Wafers from the same ingot as used in the investigation described above were used.



**Figure 3:** Wafer flexibility change as a function of thickness. The increase in flexibility is a factor 2.5 for the 150 μm wafers compared to 330 μm thick wafers.

Texturing is becoming more and more important for increasing the efficiency of mc-Si solar cells in an industrial process. One of the most promising texturing techniques on mc-material is isotropic etching with HF, HNO<sub>3</sub> and organic additives. A new recipe without organic residues was found by Hauser et al. which leads to comparable improvements in reflection and I-V characteristics [5]. This texturing recipe is less critical during etch process and easy to handle which makes it well suited for an in-line process. If thin wafers are to be used in industry with an isotropic texturing it is most important to know about the stability change after texturing. Former work showed a stability decrease after wafer texturing [4]. Stability measurements were performed on wafers of different thicknesses that were isotropically etched with a new etching process in a Rena

in-line etch system, and the results are shown in figure 4. Most data points show an average of 3-5 wafers.



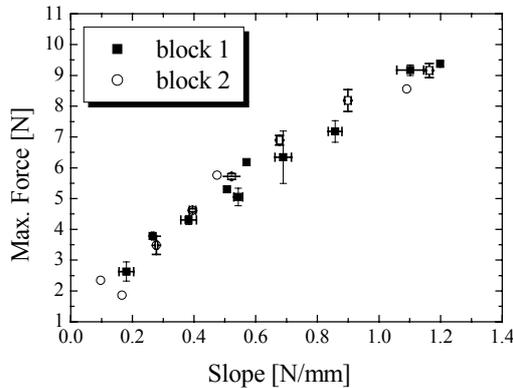
**Figure 4:** Fracture force measured with the Twist-Tester setup for wafers with varying thicknesses. The measured wafers were as-cut, iso-textured and alkaline etched.

Compared to the as-cut wafers, the benefit of alkaline etching was approximately 30-50% whereas the stability increase for the iso-textured wafers was 10-50%. The results show that, with the new recipe for texturing, the gain in stability is comparable to the gain for the alkaline etched wafers, showing that saw damage removal was well achieved by this simultaneous "soft" texturing. This result is very important for the solar cell processing if the production yield should not be diminished by using thinner wafers with iso-textured surfaces.

The obtained data in Twist-Tests are the fracture force, maximum displacement and a calculated slope from this data. Existing cracks in wafer material would result in a changed material stiffness with an effect on the data slope which should be possible to measure if data variation is not too large. Simulation work was performed to investigate the effect of cracks in silicon wafers on the measured slope in a Twist-Test-experiment [6]. The aim of this work was to apply a constant force to each wafer and thereby determine the slope and to use this slope as a crack indication. From the simulations, we found that data scattering and material parameter variations would prevent early crack recognition. The presence of cracks, depending on their size, had only a small effect on the slope. We then considered if fracture forces could be predicted by measuring methods. Under the circumstances of the Twist-Test, the slope is strongly dependent on the wafer thickness, whereas the thickness has a linear correlation with the stability. Therefore, it is expected that the slope is proportional to the fracture force. The accomplished experiments show this behaviour in very good agreement with the theory (figure 5). With increasing slope, we measured an almost linear tendency for higher fracture forces. This result is very important, as it gives the cell producer a tool to predict fracture forces. Nevertheless, it should be noted, that material parameter variations lead to different slopes and if cracks are present wrong estimations would be made.

We see a good chance that, even under production conditions, the slope could be used to find fracture forces, if material learning curves are introduced, such as measuring the maximum force and displacement for wafers of different thicknesses and calculating the slope from this.

Restrictions are given by natural fluctuations, such as grain size, local thickness variations and measuring errors. This effect is emphasized by the standard error bars of figure 5. Fracture force prediction is therefore only possible if the change in thickness exceeds certain ranges. Otherwise, all data inside the thickness error must be assigned to the same fracture force, which prevents correct prediction results.



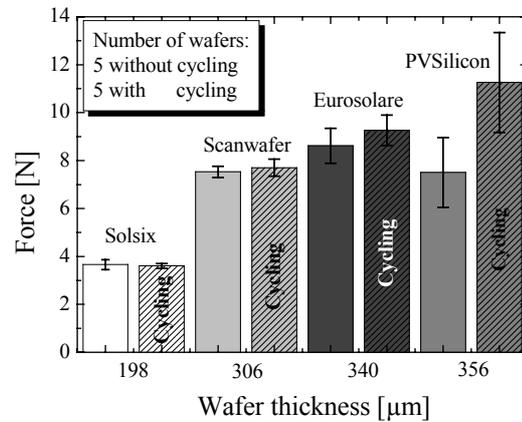
**Figure 5:** Fracture force dependence on the calculated data slope. The data shows that fracture force prediction is possible for wafer material with the restriction that cracks are not present.

In addition to the fracture force prediction, the Twist-Test can be used to sort out cracked wafer material before any process step is applied. This offers the chance to reduce the breakage rate in production and result in a higher mechanical yield in production lines. As in the case of the fracture force prediction, the wafer would be stressed up to a certain force, at which breakage for cracked wafers would occur. One difficulty is to find this measuring force in order to both enable fast measurement and prevent uncracked wafers from being rejected. The differences in fracture force for varying mc-wafers of different producers requires new adjustments when changing the wafer producer, as the fracture force can vary in the range of several Newtons.

As this method is not contactless, it could be argued that the wafer is harmed by the measurement. In this case, a mechanical yield increase could not be expected. To study if the method induces cracks, cycling tests with different mc-wafers of size  $12.5 \times 12.5 \text{ cm}^2$  and varying thicknesses were performed. Mc-material from four different wafer producers was used. Each material test consists of 10 neighbouring wafers, whereby 5 wafers were twist-tested up to breakage. The lowest fracture force required to break a wafer was then reduced by 10% and used as the upper force of the cycling test. The cycling test was then applied to the remaining 5 wafers using a lower force of 1 N and the upper force as determined by the break test. The cycling was performed 1000 times at a speed of 1 cm/s. After the cycling procedure, the wafers were twist-tested to fracture. In no cases could we report any effect of cycling on fracture force (figure 6) even for wafer material with uneven as-cut surfaces as was the case for the PV Silicon material. The lower fracture force for the Solsix material is a result of the reduced wafer thickness.

The results give us a first confirmation that the measuring method is not damaging the wafer material or

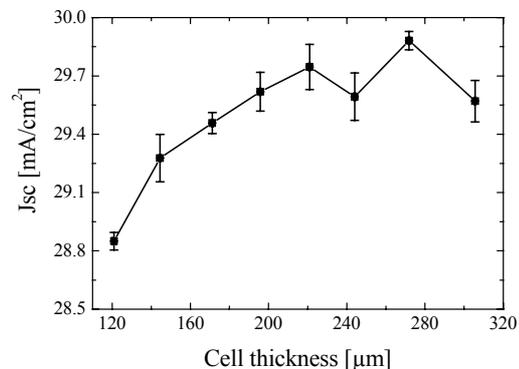
that the damage is low enough so that the influence on fracture force is negligible. A more exact statement requires a large number of wafers and cycling tests in conjunction after process steps.



**Figure 6:** Results of cycling tests for the four different mc-wafer materials (wafer producers). For each group five wafers were used for averaging.

### 3 ELECTRICAL CHARACTERISATION

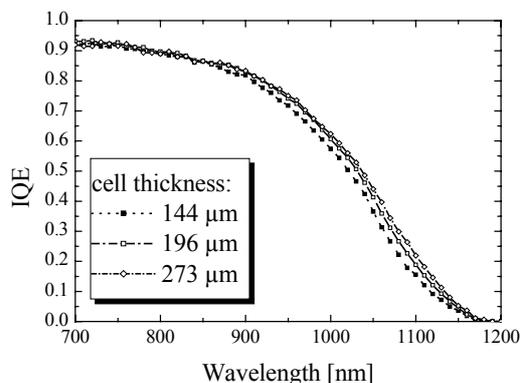
Neighbouring wafers with a thickness range of 140–330  $\mu\text{m}$  were processed in a standard industrial solar cell process sequence. We used 3–6 wafers per thickness group. The difference in wafer number resulted from a high breakage ratio during the process steps. We applied a standard industrial cleaning (NaOH, HCl, HF) and a  $\text{POCl}_3$  emitter of 35 Ohm/square. The front side was screen printed with standard silver paste, and commercial aluminium paste was used to print the rear side. The wafer material was multi-crystalline Solsix, sized  $10 \times 10 \text{ cm}^2$ . One of the major problems during this experiment was to determine if all cells could be fired under the same firing conditions. It was assumed, that fire parameter optimisation would be necessary to gain comparable results. Due to the small number of wafers available the decision was taken to fire all cells with the same firing parameters optimised for the middle range.



**Figure 7:** Short circuit current behaviour of solar cells with different thicknesses. The drop in current is mainly due to a lower IQE at higher wavelengths.

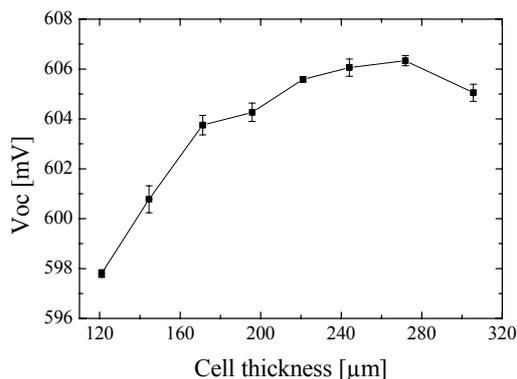
The light IV, dark IV and  $J_{sc}$ - $V_{oc}$  curves of all cells were measured and  $R_{shunt}$  and  $R_{series}$  values were fitted from these curves. From this data we could state, that even the thinnest wafers were not fired too hot, which

would create shunting and these results are therefore comparable to the other cells. For the thicker cells, the series resistance indicates that the firing through process was performed successfully. Concerning the fill factor, we found that it was stable for all cells down to 170  $\mu\text{m}$ . Below this, a drop of 1-2% was observed. This effect is due to a higher first and second diode current as well as a higher series resistance for the thinner cells.



**Figure 8:** Internal quantum efficiency for three solar cells of different thicknesses. A lower IQE especially for longer wavelengths could be observed for thinner cells.

The cell results showed a decrease in efficiency of almost 1% absolute for the thinnest cells in comparison to cells of 315  $\mu\text{m}$  thickness. In this range, the short circuit current drops by 0.7% absolute, as shown in figure 7. This decrease is explained by a lower internal quantum efficiency (figure 8) for the longer wavelengths. Firstly, the effective diffusion length, which is always larger than the cell thickness shows an increasing correlation with the cell thickness. This implies that the effective recombination velocity at the back side is limiting  $L_{\text{eff}}$ . A second effect is the reduced absorption for longer wavelengths due to the thinner wafer. This could be compensated by the use of better back surface reflectors.



**Figure 9:** Open circuit voltage of solar cells with varying cell thicknesses.

The measured  $V_{\text{oc}}$  drops by almost 8 mV for the 120  $\mu\text{m}$  thick solar cells. Figure 9 shows the measured  $V_{\text{oc}}$  values.

Tool et al. performed PC1D simulations in combination with experimental studies on multi-crystalline wafers of different thicknesses [7]. They reported that if the effective diffusion length is larger than the cell thickness and the effective rear side

recombination velocity does not exceed a given value, open circuit voltage decreases for thinner cells. Our spectral response measurements were used to calculate the effective diffusion length from the IQE. We found, that for all measured cells, the diffusion length was larger than the cell thickness. Regarding the effective rear side recombination velocity, former investigations showed that a lower limit is between 1000-1300 cm/s, which allows  $V_{\text{oc}}$  to decrease with decreasing cell thickness.

#### 4 SUMMARY

Mechanical stability tests were performed to investigate the influence of wafer thickness on fracture force. The results showed a strong decrease of stability for thinner wafer material and emphasize the necessity of crack detection, especially for thin wafers. With the calculated slope we found a possibility to predict fracture forces. Providing the material is not cracked, the breaking force for neighbouring material can be predicted. Cycling tests showed no influence of this measuring method on wafer stability. Alkaline etching and the application of isotropic texturing with a new recipe increased stability in the range of 10-50% for different thicknesses.

The presented experimental IV data emphasizes the necessity of modified solar cell concepts if thin wafer material is to be used. Even if the decrease in  $V_{\text{oc}}$  could not be prevented, the drop in current could be minimised by applying a back surface reflector. This task could not be performed with current standard aluminium rear side metallization. Further improvements on paste and cell concepts have to be performed.

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