Presented at the 20th European Photovoltaic Solar Energy Conference and Exhibition,
Barcelona, Spain, 6-10 June 2005

QUANTIFYING SURFACE DAMAGE BY MEASURING MECHANICAL STRENGTH OF SILICON WAFERS

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ABSTRACT: Ring on ring test geometry reveals the great importance of the saw damage on the mechanical stability of as-cut and textured wafers. The initial surface defects make big and unexpected differences in the strength after a standard industrial acid etch. The measuring technique is very sensitive to the surface of the wafers rather than the edge. The influence of bulk defects is excluded too, by analysing the strength of wafers from different manufacturers. It permits to focus on the modification of mechanical stability by adaptations of, e.g., wafering or chemical treatment. The apparent critical crack length is introduced as an intuitive parameter to quantify the surface damage.
Keywords: Mechanical stability, Wafering, Texturisation

1 INTRODUCTION

In the present economic context of the photovoltaics industry the reduction of the wafer cost is one of the main targets. This could be achieved by an increase of the wafer size, decrease of the thickness and a lower kerf loss. However, these changes could lead to an increase of the breakage risk reducing yield of solar cell and module processes. The mechanical properties of multicrystalline silicon wafers are influenced by several mechanisms, e.g. surface damage, edge damage, surface structure. The mechanical properties can be detected in different ways. The bending breakage tester gives the possibility to measure the maximum force necessary to break the wafers and it is one of the most common systems to check the mechanical stability. It is used by several research institutes and universities as well as by several wafer manufacturers. In this paper we use the bending breakage tester in a configuration exclusively sensitive to surface damage, and use it to analyse differences between wafers and surface treatments.

2 INSTRUMENT AND MEASUREMENT DESCRIPTION

Wafer strength is measured by applying an increasingly stronger force until the wafer breaks, recording the maximum value of force applied and the maximum wafer displacement.
For the experiments reported here a geometry of the instrument was chosen which is sensitive to the surface damage only and not to the edge damage. The best geometry that takes into account the effect of the (centre) surface of the wafer rather than the edge is the ring on ring bending tester [1]. In our case the instrument consists of a support ring with a diameter of 80 mm, and a ring of half that diameter to apply the load. The breakage force and its correlations to e.g. sawing defects or a surface etch give important information on the effect of sawing and surface treatment on mechanical stability.
Unless otherwise noted, all wafers in this study are mc-Si 125 mm square size, and 200 µm thick provided by two manufacturers (A and B).

2.1 Sensitivity to centre versus edge of wafer

In order to determine the sensitivity of the test geometry to different areas of the wafer we made cracks and scratches in different regions of sample wafers (Fig.1). We used neighbouring as-cut multicrystalline silicon wafers of 200 and 330 µm thickness. Large cracks located along the edge of the wafer do not produce a significant decrease in the breakage force, in contrast to small cracks or scratches located in the centre, i.e., within the support ring, of the wafer (Table I).

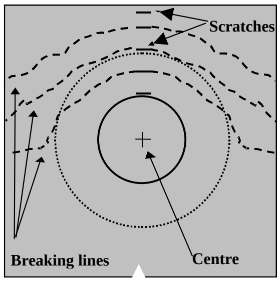

Figure 1: Sensitivity to the location of the damage

The scratches in the centre were made using a diamond tip and a metal cutter. In both cases the curves along which the wafers break start from the scratch in the centre of the wafer and finish at the edge. All the wafers broke in a maximum of 5 pieces. The breakage force for wafers with a scratch in the centre is less than 8 N while for an as-cut wafer or a wafer with large crack on the edge (Fig. 1) the maximum force is greater than 20 N. The value of breakage force for scratched wafers varies considerably from wafer to wafer. Table I reports the values of breakage force for different scratches. The scratches were identified by their length only.

Description	**Force** Max 20 N
As cut	unbroken
Crack ~3 mm in the edge	unbroken
Scratch ~2 mm in the centre with diamond tip	5 N
Scratch < 1 mm in the centre with diamond tip	7 N
Scratch ~ 3 mm in the centre with a cutter	4 N

TABLE I: Sensitivity to the inner area of neighbouring mc-Si wafers, 125 mm square and 330 µm thick

We also checked the dependence of the breakage force on the distance of the scratch from the edge. We used 6 neighbouring multicrystalline wafers. By means of a diamond tip we made scratches of about 3 mm length at different distances from the edge of the wafers (Fig. 1).

The results are displayed in Table II.

Description	**Force** Max 20 N
As cut	unbroken
Scratch ~ 3 mm at a dist. < 1 cm	unbroken
Scratch ~ 3 mm at a dist. of 1 cm	broken ~ 20 N
Scratch ~ 3 mm at a dist. of 2 cm	broken ~ 20 N
Scratch ~ 3 mm at a dist. of 3 cm	10 N
Scratch ~ 3 mm at a dist. of 4 cm	8 N

TABLE II: Sensitivity to the location of the damage for 200 μm 125 mm square mc-Si wafer

The breakage force of the wafers is greater than 20 N if the scratches are situated outside the support ring diameter (dotted circle in Fig.1). The breakage force is about 10 N if the scratches are situated inside this area.
An interesting behaviour is the way in which these wafers break. As seen in Fig. 1 the curves along which the wafers break start from the scratch location and follow a curve to the edge. This behaviour is due to the circular stress distribution in the wafer. The overall stress is maximum inside the loading ring area, and it decreases quickly outside the loading ring radius [2].

3 AS-CUT MULTICRYSTALLINE SILICON WAFER RESULTS AND BREAKAGE MODES

We performed an experiment to determine scatter in measured breakage forces, using 10 as-cut neighbouring wafers produced by manufacturer A. The maximum force is recorded for each wafer. The breakage forces observed are quite scattered giving a standard deviation of 10 N on an average of 37 N (Table III, first row). However, looking at broken wafers we recorded different modes of breaking: wafers that break in a few big pieces and wafers that break in many small pieces. Thus we separate the wafers into two categories: i) breaking in 10 pieces or less and ii) in more than 10 pieces. The wafers of the first category broke with a low force whereas the wafers belonging to the second category need much more force to break. We link the behaviour of the first category to some incidental damage in the wafers' surface which is not directly representative for the overall material and surface characteristics. Taking into account this behaviour and excluding the wafers of the first category, the average breakage force increases to 42 N and most important, the standard deviation decreases to a value of 6 N as shown in Table III.

125x125 200μm mc-Si	**Average max force**	**Standard Deviation**	
All samples	37 N	10 N	27%
Samples broken in >> 10 pieces	42 N	6 N	14%

TABLE III: As-cut multicrystalline wafers: average breakage force and standard deviation

The behaviour outlined above shows one limitation of the bending breakage instrument: the maximum force to break the sample is exactly the force needed to release the weakest mechanism in the region of maximum stress. In the first category of fracture (around 10 pieces) some damage into the wafer surface weakens it (we noted a great sensitivity of the measurement to whatever scratches) and this is the main reason why it broke at a lower force. For samples belonging to the second category we do not have an exact explanation. However, the increased breakage force could be a cause of an instantaneous propagation and multiplication of cracks in the entire wafer. Hence, we should take into account the numbers of pieces in which the wafers were broken. Then, it is possible to detect and exclude the wafers with serious local surface damage, which are not representative of the overall surface characteristics.

4 CRITICAL CRACK LENGTH AS A MEASURE OF SURFACE DAMAGE

In order to quantify the surface damage we propose the critical crack length as a parameter that gives an indication of the maximum size of the cracks present in the wafer surface. We used elements of fracture mechanics [3] to determine this crack length.
Silicon shows elastic behaviour and almost no plastic deformation before breaking at room temperature. Brittle fracture takes place when the applied stress at the tip of one crack (e.g. a micro crack due to saw damage) reaches a critical value. The stress in an element located at (r, θ) close to a crack tip can be written as [3]:

$$\begin{bmatrix}\sigma_x\\ \sigma_y\\ \tau_{xy}\end{bmatrix} = \frac{K}{\sqrt{2\pi r}}\cos\tfrac{\theta}{2}\begin{bmatrix}1+\sin\tfrac{\theta}{2}\sin\tfrac{3\theta}{2}\\ 1-\sin\tfrac{\theta}{2}\sin\tfrac{3\theta}{2}\\ \sin\tfrac{\theta}{2}\cos\tfrac{3\theta}{2}\end{bmatrix}$$

where r is the distance from the tip, θ is the azimuth and K is the stress intensity factor $K_I = \sigma Y\sqrt{\pi a}$. K is a function of the overall stress σ, the crack length a and the configuration factor Y that reflects the geometry and the loading. The index I stands for the tensile mode in which the stress is applied in the normal direction to the faces of the crack. This mode is the overwhelming majority of actual situations involving cracked components.
A crack begins to propagate when the stress intensity factor reaches a critical value. The critical value is a material dependent parameter and is called fracture toughness K_{Ic} (0.93 ± 0.3 MPa·m$^{0.5}$ on {111} plane and 0.89 ± 0.3 on {110} plane for monocrystalline silicon material at low temperature [4]). Knowing the fracture toughness of the material and the maximum stress applied, it is possible to calculate the critical crack length a. A crack becomes critical when the corresponding stress intensity factor is equal to the fracture toughness K_{Ic}. The critical crack length, however, is an estimate of the actual cracks present and it has an intuitive connection with the surface roughness. It has a quantitative value only if compared under the same geometrical conditions for the samples and the measurement. We call the extracted parameter as the *apparent* critical crack length because the geometrical conditions are not precisely known in real experiments.
In the calculation of the stress σ we make use of the linear plate theory [2] in which the middle plane of the wafer remains neutral during bending. In practise this condition is not completely satisfied and this leads to an overestimation of σ.
The aim of the following experiments is to detect

differences in mechanical stability of wafers cut with different sawing parameters. In order to check the capability of the instrument and the geometry adopted and to verify the values of critical crack length extracted we performed an experiment using different surface treatments.

4.1 Calculation of the critical crack length for different surface treatments.

We used 24 neighbouring multicrystalline wafers provided by B. Three out of four groups were treated with different chemical etching as shown in Table IV.

All the wafers showed saw marks along the overall surface. The saw marks look like straight parallel lines with step height ranging from 10 to 30 µm. However, it is difficult to quantify their number and their density. In Table 4 the measured average breakage force, the average breakage stress localised inside the loading ring and the extracted critical crack length (using K_{Ic} = 0.9 $MPa \cdot m^{0.5}$) are reported.

Group	As-cut	Saw damage etch	Polish etch	Polished + defect etch
Wafers #	10	2	10	2
Thickness	195 µm	168 µm	147 µm	~150 µm
Average force N	29±(7%)	57±(3%)	72±(31%)	23±(13%)
Average σ_{max} N/m^2	5.6×10^8	1.5×10^9	2.4×10^9	7.4×10^8
Critical crack length	0.8 µm	0.12 µm	0.04 µm	0.5 µm

TABLE IV: Surface effects on the breakage force (B wafers). In brackets the standard deviation (%). σ_{max} is the maximum stress which occurs in the wafers (the fracture stress).

The as-cut wafers broke with an average force of 29 N and the critical crack length is 0.8 µm. These wafers have more than two times bigger micro cracks than the set of as-cut wafers reported in Table III. The difference can be explained by a different saw damaged surface (including saw marks) and/or different crystal defects in the bulk.

The breaking force is more than doubled (72 N) by polishing the saw damaged surface, even though the wafers become 25% thinner due to the polishing etch. The crack length (0.04 µm) is more than an order of magnitude smaller than before the etch. However the standard deviation of the breakage force increases due to the stronger breakage force and to the possible presence of non-removed cracks.

Alkaline saw damage etching leads to a smaller but still significant reduction of the maximum crack length.

The defect etch, after polishing, leads to a remarkable increase in the apparent crack length. This treatment exposes the dislocation structure from the polished surface. Apparently, the etched defects are nucleation points for fractures.

In conclusion the experiment showed quantitatively the effect of the saw damage on the mechanical stability of the wafers. We have determined that by removing the saw damage from the wafers the mechanical stability is doubled. This is made possible by using ring on ring breakage tester, which excludes the wafer edge from the measurement.

4.2 Industrial acid etching

Another set of 20 neighbour wafers provided by B were compared after processing with ECNs' industrial acid etching and an alkaline saw damage etching.

The wafers were dividend in 4 groups processed in different ways, as shown in Table V.

Group	As-cut	Saw damage etch	Industrial acid etch T1	Industrial acid etch T2
Wafers #	5	5	5	5
Average force N	30±(9%)	64±(8%)	73±(7%)	54±(18%)
Average σ_{max} N/m^2	5.5×10^8	1.8×10^9	1.6×10^9	1.2×10^9
Critical crack length	0.8 µm	0.08 µm	0.1 µm	0.2 µm

TABLE V: Mechanical stability after industrial acid etching of B wafers. T1 and T2 correspond to the different etching time.

The aim of this experiment is to look at the effect of ECNs' industrial acid etching on the mechanical stability of the wafers. We used two different etching times. One is the ECN standard recipe currently used in industry and the second is the same but with double etching time. For comparison also results of as-cut wafers and alkaline etched wafers are shown.

The results for the as-cut wafers and after saw damage etching are consistent with Table IV. This reveals no influence of the saw marks on the wafers' strength. However their complete physical characterisation remains necessary.

The T1 recipe has a very positive effect on the mechanical stability of the wafers. The stress applied to break the wafers is 3 times greater than for as-cut wafers and the critical crack length is almost ten times smaller. The results are comparable to the saw-damage etch and approach the strength after polishing etch in Table IV, (note that compare stress or crack length should be comparable, rather than force, to account for thickness variations).

That the strength after alkaline saw-damage removal and acid etch is comparable is somewhat counterintuitive. One would expect that the more pronounced surface texture after acid etch would weaken the wafer. A detailed analysis on the surface structure should be carried out to resolve this.

We see a weakening of the wafers when the acid etching time is doubled. A dislocation structure appears on the front surface of the wafers. As seen also in the previous experiment (Table IV) these areas can be nucleation points for breakage. An important result is that for these wafers the etching time for best electrical cells properties ($J_{sc}xV_{oc}$) is also good for better mechanical properties.

A similar experiment was performed on wafers of same size and thickness but from a different manufacturer (A). Each wafer comes from a different position in the ingot and it is neighbouring to the corresponding wafer in each group.

Group	As-cut	Saw damage etch	Industrial acid etch T1
Wafers #	15	15	15
Average force N	43±(18%)	57±(8%)	43±(17%)
Average σ_{max} N/m^2	8.4×10^8	1.5×10^9	9.7×10^8
Critical crack length	0.4 μm	0.1 μm	0.3 μm

TABLE VI: Mechanical stability on wafer type A.

The as-cut wafers present a higher mechanical stability than the type B as-cut wafers (Tables IV and V). The average stress applied to break them is 40% higher and the critical crack length is half that of the corresponding B wafers.

After the alkaline saw damage etch the fracture stress is about $1.5\text{-}1.8\times10^9$ N/m^2, the same as for the type B wafers in table IV and V. Such an etch is probably not, or only weakly, dependent on the initial condition of the surface. This shows that type A and type B wafers are intrinsically of similar strength. Therefore we can exclude the influence of a bulk defect in comparing results on type A and type B wafers, or at least such an influence is included in the variation we obtain (3×10^8 N/m^2).

The first conclusion is, therefore, that type A wafering has apparently resulted in less surface damage than the type B wafering. A further work would be to correlate the strength of as-cut wafers with the sawing parameters used (e.g. SiC diameter).

When the type A wafers are treated with the T1 industrial acid etch the strength differs strongly from the experiment in Table V. Whereas Table V showed a remarkable increase in σ_{max}, in this case we have only a slight increase (15%). As mentioned above, it is likely that the two kinds of wafers have a different amount and/or type of saw damage. Type B *as-cut* wafers are *weaker*, e.g., due to the presence of deeper defects. After T1 acid etching, the type B wafers are *stronger*.

The difference in the strength after acid etching for the two manufacturers should be addressed to the different defect structure present on the surface because the intrinsic strength of the wafers is the same. Optically they look similar (comparable surface reflectance). The acid etching therefore has the effect to remove the more effective defects better from wafer type B compared to wafer type A (effective from the mechanical stability point of view).

We conclude therefore, that the initial defects make large and unexpected differences in the strength after T1 acid etching.

A remark should be made for the comparison of experiments in Table V and VI. The T1 acid etching results in one side of the wafers being rather uniform (what we call front) and the other side with some defects. In Table VI the type A wafers were broken with the front side up. Hence the loading ring applies a force on the front and opens the defects present on the backside of the wafers. In Table V, the B wafers were broken with the front side down. An experiment was carried out to quantify this effect, using 10 neighbour A wafers. The wafers received the industrial acid etching T1 and half of them were broken with front side up and half with front side down. Results are shown in Table VII.

Group	Front side up	Front side down
Wafers #	5	5
Average force N	37±(7%)	43±(6%)
Average stress N/m^2	7.8×10^8	9.1×10^8
Critical crack length	0.4 μm	0.3 μm

TABLE VII: Mechanical stability on acid etched type A wafers broken with front side up and front side down.

The force applied to break the same wafers differs by 6 N (15%). This means that the defects on the backside have a limiting impact on the wafer strength, though not sufficient to explain the difference between type A and B wafers.

However this difference is not generally valid and depends on the defects in the rear side.

5 CONCLUSIONS

A ring-on-ring bending tester is very sensitive to surface damages on multicrystalline silicon wafers, and not noticeably to even severe damages in the edge region. This permits to quantify the effect of saw damages as well as etching treatments on the mechanical strength independently of edge damages. To quantify surface damage we propose the apparent critical crack length, which gives an indication of the maximum size of the cracks present in the wafer surface.

There is an inverse correlation between strength as-cut and strength after acid texturisation, which needs to be investigated further. The intrinsic strength of wafers from two different manufacturers was found to be similar, as the alkaline saw damage etch has revealed.

In conclusion we can state that the saw damage has a large effect on the mechanical stability of as-cut wafers but also on the mechanical stability of acid etched wafers. The acid etching time for best electrical cells properties is also good for better mechanical properties.

6 ACKNOWLEDGEMENTS

This work is part of the FP6 CrystalClear project and funded by the European Commission under Contract number SES6-CT_2003-502583. We thank the wafer manufacturers for providing us testing materials.

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