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MECHANICAL STRENGTH OF SILICON WAFERS AND ITS MODELLING

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ABSTRACT: Mechanical strength measurements of multicrystalline Si wafers are carried out with a ring-on-ring test geometry. This geometry is very sensitive to the surface of the wafers rather than the edge. The measurements reveal the great importance of the saw damage on the mechanical stability of as-cut as well as textured wafers. The initial surface defects make a big and unexpected difference in the strength after a standard industrial acid etch. The strength analysis of wafers from different manufacturers shows no influence of bulk defects on strength. This geometry therefore permits to focus on the modification of mechanical stability by adaptations of, e.g., wafering or chemical treatment. The stress at breakage is translated into an apparent critical crack length, which can be used as an intuitive parameter to quantify the surface damage. The relationship between breakage force and wafer thickness from linear plate theory is analysed and verified.

1 INTRODUCTION

In the present photovoltaics industry the reduction of the wafer and cell 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 wafering, solar cell, and module processes. The mechanical properties of multicrystalline silicon wafers are influenced by several parameters and defects, e.g. surface damage, edge damage, surface structure.

The mechanical properties can be detected in different ways. A bending breakage tester [1] gives the possibility to measure the maximum force necessary to break the wafers. 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 geometry exclusively sensitive to surface damage (rather than edge damage), and use it to analyse differences between wafers and surface treatments.

2 INSTRUMENT AND MEASUREMENT DESCRIPTION

Wafer strength is measured in a bending breakage tester 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 geometry that is most sensitive to the wafer surface is the ring on ring bending tester [1,2]. 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 loading stress is localised inside the loading ring. 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. They were provided by two manufacturers (A and B).

3 THEORY AND MODELLING

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 theory from fracture mechanics [4] 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 [4]:

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

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 stress magnitude 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 [5]). Knowing the fracture toughness of the material, and the stress resulting in breakage, it is possible to calculate the critical crack length a, for which the stress intensity factor is equal to the fracture toughness K_{Ic}. The critical crack length 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 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 [3] in which the deflection of the wafer is small compared to wafer thickness. In practise this condition is

not completely satisfied. However, it still allows comparison of wafers with similar thickness.
In order to predict the mechanical stability of thinner wafers the relationship between the breakage force and the thickness of wafer have to be investigated. The relation we want to proof experimentally follow by:

$$\sigma_{max} = \frac{K_{Ic}}{Y\sqrt{\pi a}} \quad (2)$$

and

$$\sigma = C\frac{F}{t^2} \text{ (in linear plate approximation)} \quad (3)$$

The maximum stress tolerable by the sample is proportional to $1/t^2$ when an equivalent crack length *a* for wafers receiving the same surface treatment is assumed.
This implies the following relationship between breakage force and thickness:

$$F_{max} = c \cdot t^2 \quad (4)$$

where $c = K_{Ic} / \left(CY\sqrt{\pi a}\right)$. In the last section this relationship is verified experimentally.

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 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 I.
All the wafers showed saw marks along the full 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 I 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·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 I: Surface effects on the breakage force (B wafers). In brackets the standard deviation (%). σ_{max} is the stress (calculated from applied force, with linear plate theory) at which the wafer breaks (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 a previous work [5]. The difference must be due to a different saw damaged surface (including saw marks) and/or different crystal defects in the bulk.
By polishing the saw damaged surface the breaking force is more than doubled (72 N), 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.
Alkaline saw damage etching leads to a smaller but still significant reduction of the maximum crack length (note that stress or crack length should be compared, rather than force, to account for thickness variations).
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 effective 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. These observations were made possible by using ring on ring breakage tester, which excludes the wafer edge from the measurement.

4.1 Industrial acid etching

Another set of 20 neighbour wafers provided by the same manufacturer B were compared after processing with ECNs' industrial acid etching and an alkaline saw damage etching. The wafers were divided in 4 groups processed in different ways, as shown in Table II.

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 II: 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. T1 is the ECN standard recipe currently used in industry and T2 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 I.
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 I.

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 I) these areas can be nucleation points for breakage. An important result is that for these wafers the etching time (T1) for best electrical cell properties ($J_{sc}xV_{oc}$) is also good for better mechanical properties.

A similar experiment was performed on wafers of the 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 III: Mechanical stability on wafer type A.

The as-cut wafers present a higher mechanical stability than the type B as-cut wafers (Tables I and II). 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 I and II. 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 II. Whereas Table II 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 carried out 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 in the surface make large and unexpected differences in the strength after T1 acid etching.

A remark should be made for the comparison of experiments in Table II and III. 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 III 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 II, 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, insufficient to explain the difference between type A and B wafers.

5 INFLUENCE OF WAFER THICKNESS ON THE BREAKAGE FORCE

We used 40 wafers from the best quality class of the manufacturer B. The quality class includes the geometric defects of the wafers such as the presence of saw marks and the total thickness variation (TTV). In this case best class means saw marks between 0 and 20 µm and TTV between 0 and 50 µm. Actually no such classification information was available in the previous experiments. The only information there was the qualitative description and height of saw marks.
The B wafers came from a different ingot than the previous experiments, were 270 µm thick and 150x150 mm^2 large. They were divided into two groups and processed with the T1 industrial acid etch and the alkaline saw damage etch with the same process parameters as the previous experiments. The results are shown in Table IV.

Group 270㎜	Saw damage etch	Industrial acid etch T1
Wafers #	5	5
Average force N	>215	125±(8%)

TABLE IV: Industrial acid and saw damage etched wafers. The first do not break with the max available load of 215N.

The saw damage etched wafers sustained a load of 215N without breaking. This was the maximum force applicable by the instrument.
It is not possible to correlate the maximum stress for these wafers with the maximum stress of the wafers in the section 4 due to the large differences in the wafer thickness. Comparisons can only be made between wafers with similar thickness due to the approximations in using the linear plate theory.
To see the influence of the thickness on the mechanical stability, Fig. 1 shows the force versus the wafer thickness.

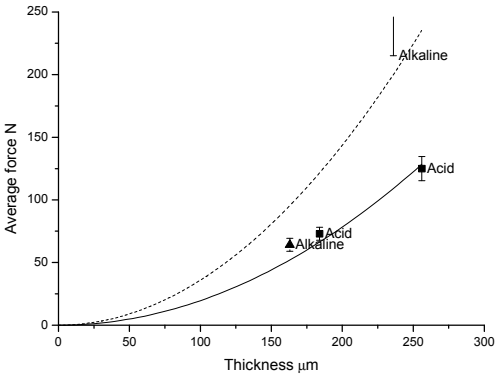

Fig. 1: Force versus thickness for saw damage (alkaline) and acid etched samples. The solid line represents the best fit based on Eq.4 for acid etched samples; the dashed line for saw damage etched.

The unbroken saw damage etched wafers are represented with an error bar starting at the maximum force applicable with our bending breakage tester (215N).
Interesting is the good agreement between the breakage force measured for acid etched wafers and a quadratic dependence on the square of thickness coming from Eq.4.
The quadratic behaviour is not clearly shown by the alkaline etched wafers. The dashed line in Fig. 1 is the best fit to the two available data points. Even though the crack length distribution should be more under control for these samples, the experimental evidence shows that Eq.4 is not fulfilled for a unique value of the constant c as for the case of acid etched samples.
We can analyse this problem by looking in more detail at Eq.3. In the relation between F and σ the geometry of the breakage tester is included. This means beside the rings diameter (support and loading one) also the wafer geometry.
Especially for alkaline samples in which the reduced crack length increases the maximum stress other effects become important. In this particular case the larger wafer size could have an influence on the stress-force relationship (i.e., $\sigma<CF/t^2$) but also the lower values of TTV and height of saw marks could increase σ_{max} (since the wafers were classified as first class material). That is the reason why the fit does not work well.
In the acid etched samples the larger crack length results in a smaller σ_{max}. This smaller value could somehow hide the effect of TTV and saw marks. Furthermore the maximum wafer deflection is less due to lower force, therefore σ is closer to the result of linear plate theory: CF/t^2 (where it is slightly dependent on wafer size). Those are the reason why acid etched samples fit well the Eq.4.

6 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.
Essential in further analysis will be the complete analysis of the actual stress force relationship by means of finite element analysis or real stress measurement. Also the breakage of samples with different and known TTV and saw marks has an important role in the understanding of the complete phenomenon. The data presented in the last section shows the importance of the alkaline etch to bring forward these second order effects.

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