Presented at the 21st European Photovoltaic Solar Energy Conference and Exhibition,
4-8 September 2006, Dresden, Germany

MECHANICAL STRENGTH OF SILICON WAFERS DEPENDING ON WAFER THICKNESS AND SURFACE TREATMENT

G. Coletti, N.J.C.M. van der Borg, S. De Iuliis, C.J.J. Tool and L.J. Geerligs
ECN Energy Research Centre of the Netherlands
Westerduinweg 3, NL 1755 ZG Petten, the Netherlands
Tel +31 224 564382 coletti@ecn.nl

ABSTRACT: Mechanical stability of wafers with thickness between 120 and 320 μm is tested with ring on ring breakage tester. A linear relationship between breakage force F and thickness is found, instead of quadratic as theory predicts. Therefore thinner wafers tolerate a higher force than expected. Thinner wafers bend and stretch due to the increased flexibility, redistributing the stress inside the wafer.
The effect of different isotexturing recipes on the mechanical stability is analysed. The resulting wafer strength distributions follow a Weibull function as expected from literature.
Keywords: mechanical stability, thin wafers, etching.

1 INTRODUCTION

In the present economic contest of the photovoltaic industry the main concern is on the supply of silicon wafers. The shortage of feedstock and its increased price result in a need to reduce the material consumption. This is mainly achieved by reducing the wafer thickness.

However, this reduction could lead to an increased chance of breaking, reducing yield of wafering and of solar cell and module processes. The mechanical stability of silicon wafers is also influenced by other mechanisms like sawing parameters, surface damage and edge damage. Their influence can be reduced by optimising or modifying the surface treatment (i.e. isotexturing).

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. 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 study the influence of wafer thickness and different isotexturing recipes on the mechanical stability.

2 MEASUREMENT PRINCIPLE

Wafer strength can be measured by loading the wafer with an increasing mechanical stress until the wafer breaks. The applied stress at the moment of breaking characterizes the wafer strength. A convenient way of applying the stress is the so-called ring-on-ring tester (see Fig. 1).

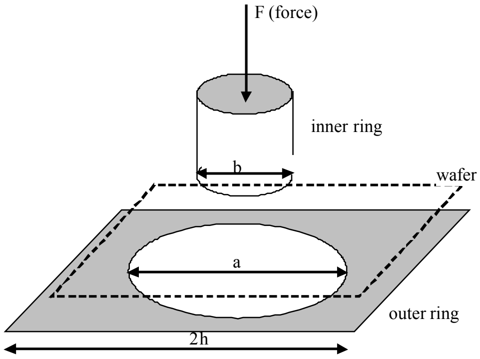

Figure 1: Sketch of the measurement geometry

With this geometry the highest stress in the wafer is introduced within the region of the inner ring and at the wafer surfaces. Outside this region the stress decreases rapidly [2], see figure 2.

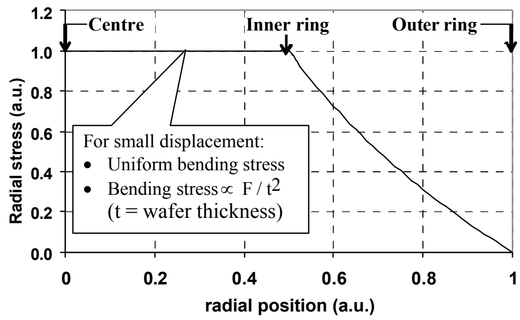

Figure 2: Radial stress distribution for small wafer displacement at the wafer surfaces.

As a consequence the measured mechanical strength reflects mainly the local mechanical properties of the wafer within the inner region and the influence of possible cracks in the wafer edges become very small [1,3]. Furthermore the stress within this inner region is uniform for small displacement, which means that the test results are determined by the weakest spot of the wafer within the inner region, regardless the exact location.

The force of the inner ring on the wafer causes the wafer to bend, which causes a tensile stress at the lower side of the wafer and compressive stress at the upper side. When the displacement of the wafer is relatively small compared to the wafer thickness, the tensile stress and compressive stress have equal magnitudes. When the displacement becomes larger than the wafer thickness, the applied force is not only balanced by the bending moment of the wafer but also by the stretching (or membrane) stress in the wafer due to the wafer edges (which cannot move freely towards the centre). This effect causes a higher tensile stress magnitude at the lower side than the compressive stress magnitude at the upper side of the wafer. In the extreme case the circumferential compression at the wafer edge may cause buckling (irregular bending of the outer part of the wafer) [7].

Smaller displacement is achieved, for a fixed stress in the wafer, by using a smaller inner ring but at cost of a smaller tested wafer area (the inner region). To counterbalance the loss of effective test area the wafer can be cut into smaller pieces. As explained above, the possible cutting damage at the edges are of no consequence to the measure breaking force with this method. An additional advantage of cutting the wafer into smaller samples is the increase of test samples per wafer, which is beneficial for the reduction of the statistical uncertainty.

When the displacement is relatively small the maximum stress can be determined very simply by measuring the applied force, without the need of laborious strain measurements. For a thin wafer and small displacement the maximum stress at the surface within the inner ring can be calculated with Eq. 1 and 2 (ref. [3,4]).

$$\sigma = \frac{3}{4\pi}\left[2(1+\nu)\ln\frac{a}{b} + \frac{(1-\nu)(a^2-b^2)}{R^2}\right]\cdot\frac{F}{t^2}, \qquad \text{Eq. 1}$$

where F is the applied force, t is the wafer thickness, ν is the Poisson's ratio, a is the outer ring radius, b is the inner ring radius and R is the equivalent wafer diameter.

For square wafers the equivalent wafer diameter is:

$$R = \frac{h(1+\sqrt{2})}{2} = 1.207h, \qquad \text{Eq. 2}$$

where h is half of the side length of the square wafer.

The fracture stress of the wafer is determined by measuring the force at which the wafer breaks and the formulas (1) and (2). Since this fracture stress is not measured directly but calculated with the assumption that these formulas are valid for the displacement that occurs at breaking, we call this the "calculated fracture stress" and we use the symbol $\sigma_{fr,calc}$.

3 RING ON RING DESIGN

The design of the rings was performed empirically using square silicon wafers of 100 x 100 mm with a thickness of 200µm. As a first choice the inner ring diameter was made 40 mm and the outer ring diameter was made 80mm, made of aluminium. To minimize the possible radial stress due to the friction between the support ring and the wafer some experiments were performed with additional ball bearings in the outer ring (90 steel balls with 3mm diameter). These balls were free to roll inside a groove around the outer ring opening. The geometry is sketched in Fig. 3.

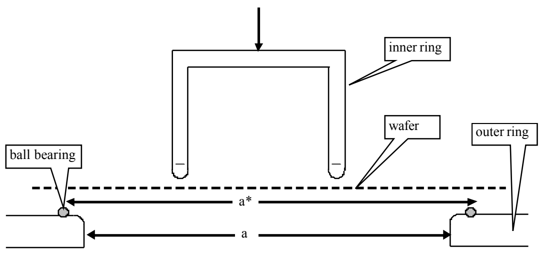

Figure 3: Sketch of the design (not to scale)

Experiments were performed with and without the ball bearings with 2 groups of neighbouring silicon wafers. To account for the small difference between a and a*, the measured fracture forces were converted into the calculated fracture stress ($\sigma_{fr,calc}$) according to section 2. The value of the Poisson's ratio was assumed to be 0.3, which is a common value for most materials. The results are given in Tab. I.

	ball bearings	
	without	with
number of wafers	10	10
thickness (mm)	0.2	0.2
width (mm)	100	100
a, a* (mm)	80	86
b (mm)	40	40
$P_{fr,avg}$ (N)	46.61	41.95
stdev (%)	11.8	13.1
$\sigma_{fr,calc}$ (MPa)	758	777

Table I: Test results with and without ball bearings

The values for the $\sigma_{fr,calc}$ for both groups are well within the standard deviations and are not significant. Therefore it was decided to continue without the ball bearings.

During each of the 20 experiments buckling was observed. Additional experiments with smaller ring diameters (40 mm outer ring and 18 mm inner ring) with 50 mm wafers of 0.2 mm thickness showed no buckling at all. For this reason it was decided to continue with the smaller rings and smaller samples (e.g. nine 50 mm samples cut out of 150 mm wafers or nine 52 mm samples cut out of 156 mm wafers).

4 MECHANICAL STABILITY VERSUS THICKNESS AND ITS MODELLING

As mentioned in paragraph 2, the proposed quantity for the mechanical integrity of solar wafers ($\sigma_{fr,calc}$) is not measured directly. In principle the stress at the lower wafer side can be measured more directly by measuring the strain and using the Young's modulus (elasticity modulus). This possibility for validating $\sigma_{fr,calc}$ was not followed. As alternative, experiments were performed with wafers from the same manufacturer but with different wafer thickness. Since the value of $\sigma_{fr,calc}$ is considered to be a material property the measurement results should be independent of the wafer thickness. Through equation 1 this can be reformulated by saying that the breakage force of a certain material should be proportional to the wafer thickness squared (for a fixed ring-on-ring geometry and a similar surface treatment [3]), see Eq. 3.

$$\sigma \propto \frac{F}{t^2}, \qquad \text{Eq.3}$$

Validation experiments have been performed using 16 wafers of 100x100mm. The wafers were all neighbouring. After an industrial isotexturing they were laser cut into 4 samples of 50x50mm. The thickness varied between 120 and 320 µm. The 64 samples were tested by the ring-on-ring facility (inner diameter 18mm, outer diameter 40mm). The displacement of the wafers at the inner ring, ranged from 0.9 (thickest wafer) to 2.4 (thinnest wafer) times the wafer thickness. This displacement is measured by measuring the displacement of the inner ring from the moment of the load onset to the moment of wafer breaking. The displacement of the centre of the wafer is obviously higher. The measured fracture force as function of the wafer thickness is given in Fig. 4. The figure shows also the best power function fit and the best quadratic function fit. Both fits are forced through the origin.

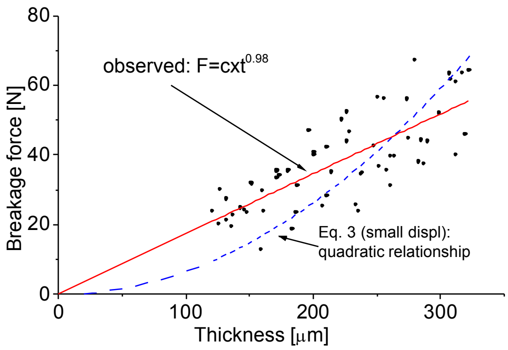

Figure 4: Measured fracture force as function of the wafer thickness including the best power function fit (solid line) and the best quadratic function fit ($F=c\times t^2$, dashed line). Both fits are forced through the origin.

Fitting the measurement data with a power function results in an almost linear relation instead of a quadratic relation. This means that Eq. 1 is not valid for the displacements that occur in the experiments.

The displacement especially in the case of thin wafer is no more relatively smaller than the thickness. This is the reason why the Eq.1 does not hold for all the thicknesses investigated. The stretching stress in the wafer due to the wafer edges cannot be neglected for these wafer thicknesses and ring diameters.

The influence of the displacement variation is to modify the proportionality factor in Eq. 3. This means that the proportionality factor is not constant once the assumption for Eq. 1 is not valid. This factor becomes a function of the displacement itself and therefore of the thickness.

This finding limits the simple application of Eq.1 to the comparison of the mechanical integrity of wafers of comparable thickness. If wafers of various thicknesses have to be compared the ring diameters must be made smaller or the stretching stress has to be accounted for (e.g. via finite element calculations).

Discussion

Does this behaviour mean that the thinner wafers are stronger than expected?

The simple model describes in [3] and recalled in this work predicts a lower breakage force for thinner wafers than experimentally found. The breakage force for thinner wafers tightens upwards showing a linear trend. This does not mean that the wafers are stronger but that the wafers support higher force before breaking. What physically happens in the wafers is a redistribution of the stress (lowering its maximum value). When the displacement becomes larger than the wafer thickness the applied force is not only balanced by the bending moment of the wafer but also by the stretching stress in the wafer due to the wafer edges. This causes a redistribution of the stress in the wafer. This is the reason why more force is necessary to reach the critical stress responsible for the breakage.

Therefore this does not mean that the thinner wafers are stronger but that in this particular geometry the wafers bend and stretch and thereby tolerate more applied force.

This is an expected behaviour of thin wafers compared to thick wafers because of their increased flexibility. The same mechanism can happen in a cell production line. The wafers, though sensitive to cracks in the edge, can tolerate higher applied force because they can shape itself to the particular force applied reducing the maximum stress at a surface.

5 MECHANICAL STABILITY VERSUS ISOTEXTURING RECIPES

One of the process steps in the production of crystalline silicon cells is chemical etching for the removal of saw damage and for the texturisation of the wafers. It is well known that etching removes a significant part of the residual stress caused by the sawing [5]. The recipe of the etching process has influence on the efficiency of the solar cells [6], on the production costs and on the environmental aspects. Furthermore the etching recipe influence the mechanical integrity of the wafers [1,2]. To investigate the latter effect experiments were performed with three etching recipes on identical wafers. The mechanical integrity of the etched wafers was quantified with the ring-on-ring instrument.

The experiments were performed with crystalline silicon wafers with a thickness of about 225μm and a length and width of 125 mm. One group of 10 wafers was etched with a standard recipe (A), another group of 10 wafers was etched with recipe B and a third group of 10 wafers with recipe C. After the etching the wafers were laser cut into 4 square samples (62.5 x 62.5 mm). These samples were tested with the ring-on-ring facility (inner ring diameter 18 mm, outer ring diameter 40 mm). Comparing the required force to break the wafers compares the effect of the isotexturing recipe on the strength of the wafers. The results are shown in Tab II. The fracture forces of the three groups were fitted to a Weibull probability function. The obtained Weibull parameters are also given in Tab. II.

	Etch A	Etch B	Etch C
Number of tested samples	74	78	75
Averaged force at breaking (N)	51.5	46.6	42.6
Weibull scale parameter λ (N)	56.7	50.8	44.6
Weibull shape parameter k (-)	4.1	5.1	11.3

Table II: measured effect of the isotexturing recipe on the wafer strength

The results show a clear dependence of the wafer strength with the isotexturing recipe.

The measured distribution of the fracture force per group is given in Fig. 5a, 5b and 5c. The distribution is presented with force intervals (bins) of 5N. For comparison with the results of the fitting, the Weibull curves were integrated over the same force intervals. The figures show that Weibull fitting seems to be appropriate for this kind of measurement data.

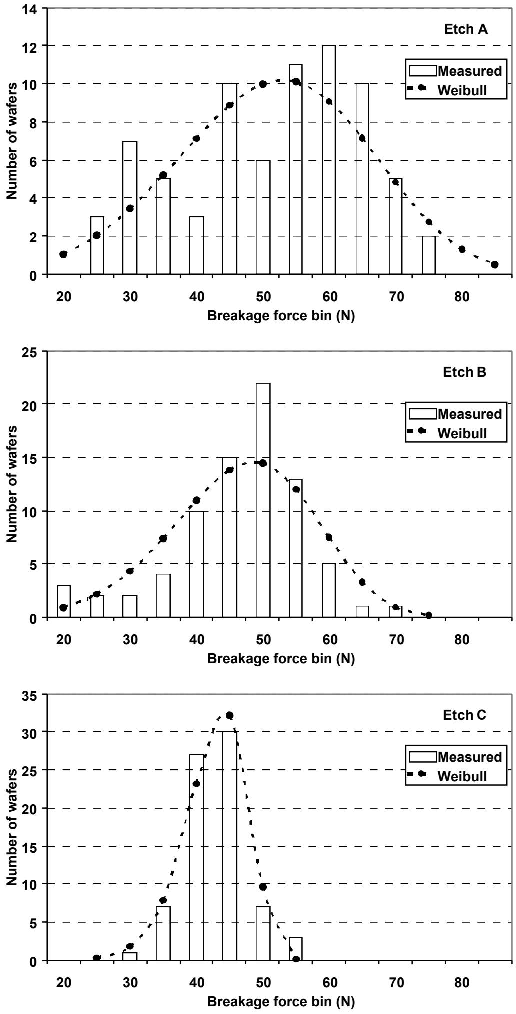

Figure 5a, 5b, 5c: Breakage force distribution for different isotexturing recipes.

6 CONCLUSIONS

The advantage of the ring-on-ring loading geometry is that the test focuses on the inner region of the wafer excluding the effect of possible cracks in the wafer edges. This permits to discriminate between cracks located in the surface and in the edges of the wafers, hence to study the effect of the surface treatments on the mechanical stability.

The equation for the fracture stress calculation is not valid for all the thickness investigated because the large displacements of the thin wafers. In order to calculate the stress in thin wafers, smaller ring diameters or a finite element calculation need to be used. Relative comparison of the mechanical integrity of wafers can be done in a simple way if the wafers have similar thickness.

The quadratic relationship between the breakage force and the thickness is not shown by the experimental data. A linear relationship is instead found. The breakage force for thinner wafers tightens upwards demonstrating that thinner wafers tolerate higher force applied than expected. This is due to the increased flexibility of thinner wafers. They can bend and stretch redistributing the stress inside the wafer. Therefore more force is needed to reach the critical stress responsible for the breakage.

The effect of different isotexturing recipe on the mechanical stability of silicon wafers was experimentally examined. The experiments were performed on three groups of about 75 samples per group. To reduce the uncertainty caused by the statistical spreading curve fitting to the Weibull probability distribution seems appropriate. The effect of the isotexturing recipe was clearly demonstrated.

7 ACKNOWLEDGEMENTS

This work is part of the FP6 CrystalClear project funded by the European Commission under Contract number SES6-CT_2003-502583.

8 REFERENCES

[1] G. Coletti, K. Tool, L. J. Geerligs, Quantifying surface damage by measuring mechanical strength of silicon wafers, 20th EPVSEC, Barcelona, June 2005.

[2] D.K. Shetty, A.R. Rosenfield, P. Mc Guire, G.K. Bansal and W.H. Duckworth, Biaxial flexure tests for ceramics, ACS Bulletin, 1980, vol. 59, n. 12, p. 1193.

[3] G. Coletti, K. Tool, L. J. Geerligs, Mechanical strength of silicon wafers and its modeling, 15th Workshop on Crystalline Silicon Solar Cells & Modules: Materials and Processes, Colorado USA, August 2005.

[4] F.F. Vitman and V.P. Pukh, "A method for determining the strength of sheet Glass", Zavodskaya Laboratoriya (Russia), vol. 29, no. 7, 1963.

[5] C. McHatton and C. M. Gumbert, " Eliminating backgrind defects with wet chemical etching", Solid State Technology, Vol. 41, No. 11, p.85, November 1998.

[6] C.J.J. Tool, P. Manshanden, A,R. Burgers and A.W. Weeber: Wafer Thickness, Texture and Performance of Multicrystalline Silicon Solar Cells, 14th International Photovoltaic Science and Engineering Conference (PVSEC), Bangkok, Thailand, 26-30 January 2004.

[7] R.J. Roark, Formulas for stress and strain, ed. 4, McGraw-Hill Book Company, 1965, p244