STUDY OF THE EDGE AND SURFACE CRACKS INFLUENCE IN THE MECHANICAL STRENGTH OF SILICON WAFERS

J. Barredo[1], L. Hermanns[1], A. Fraile[1], J. C. Jimeno[2] and E. Alarcón[1]
Author for correspondence: Josu Barredo
[1]Department of Structural Mechanics and Industrial Constructions, Polytechnical University of Madrid, c/ José Gutiérrez Abascal 2, 28006 Madrid, Spain. Tel: +34-91-336-53-46, email: jbarredo@etsii.upm.es
[2]Microelectronic Technology Institute, Basque Country University-Engineering School, Alameda de Urquijo s/n, 48013 Bilbao, Spain, email: jc.jimeno@ehu.es

ABSTRACT: The objective of the present study is the estimation of the depth to which the wire sawing process causes damage to the wafer surfaces. Previous analyses were carried out by means of the four line bending test. The characteristic of this test implied that the failure could be due to surface cracks located in the central zone of the wafer or near the edges. In order to evaluate the influence of the edge or surface cracks a new study has been carried out using the ball/ring on ring test. Description and results of the tests are presented. The preliminary analysis of the failure stress using analytical methods confirms the expected results. A Finite Element model developed to get more information of the test results is also presented.
Keywords: Cost reduction, Defects, Characterization

1 INTRODUCTION

The use of thinner wafers is commonly accepted as a clear way to reduce the cost of solar panels. However, thinner wafers present different mechanical properties and PV industry needs a thorough knowledge of them. Many studies concerning the mechanical properties of silicon wafers have been carried out last years [1], [2], [3], [5] and [7].

Many cracks are produced in the cutting process of the ingot,. A clear way to reduce the breakage rate in the production process is to remove the most damaged superficial layers. Therefore, the estimation of the damaged depth becomes a very useful information [1].

The ball/ring on ring test has been employed and the results obtained have been compared with those obtained in previous studies when the four line bending test was used. The characteristic of the ball/ring on ring test implies that the failure is due to cracks located in the central zone of the wafer. It's expected a smaller depth results than for the four line bending test since in the previous case both edge and surface cracks may have caused failure [2], [3].

2 OBJECTIVE

As already mentioned, previous studies by the authors [1] concerning the thickness of the damaged layer due to the wire sawing process were carried out by means of the four line bending test. For comparison, the mechanical strength has been represented versus the decreased thickness per face (figure 1).

According to figure 1, it seems that from 30 μm per face of decreasing thickness, the strength keeps a constant value. Therefore, it could be concluded that cracks produced in the wire sawing process reside in the most superficial layer and it has a thickness of approximately 30 μm.

Some authors suggest that the depth of the damage is up to 15 μm [4] and [5]. The damaged depth by the wire sawing process depends on many parameters like the number of uses of the wire or the velocity of the cutting process.

Anyway, it's suspected that the damage caused by the wire sawing process is higher near the edges than in the central zone of the wafer. In order to assess this hypothesis, the influence of surface and edge cracks in the mechanical strength has been studied.

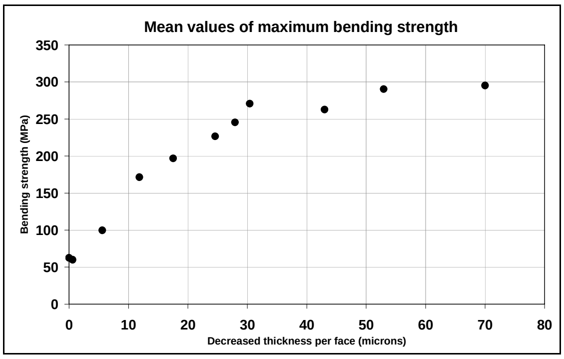

Figure 1: Strength versus decreased thickness

3 THE BALL/RING ON RING TEST

3.1 Comparison with the four line bending test

It's known that the failure in wafers is due to the combination between the stress state in the wafer and the cracks existing inside them [1], [2]. In the four line bending test (figure 2) the stressed zone between the supports extends over the whole wafer.

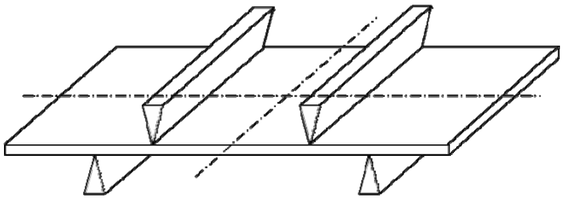

Figure 2: The four line bending test

Cracks located in the central zone and near the edges are able to cause the wafer failure. So, the results of the tests include both failure mechanisms.

In the ball/ring on ring test, stresses near the central zone are much higher than borders stresses, so the failure is due to surface cracks in the central zone [2] [3].

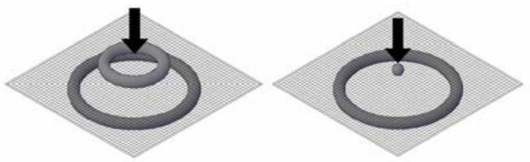

Figure 3: Ring-on-ring and ball-on-ring test

The direct comparison of stress results between the two tests is not possible without considering the size effect. As already has been mentioned, the wafer strength depends on the stress level and the corresponding critical crack size. So the bigger the stressed zone the higher is the probability to find a critical crack in it. For this reason, the results must be referred to a reference area before comparison.

In spite of this, there are other types of results that can be extracted from the tests without taking into account the size effect. A similar curve as the one presented in figure 1 should be obtained when employing the ball/ring on ring tests. Although the values in mechanical strength may be different, the thickness of damaged surface could be obtained. This result may explain the different values observed in the literature about the depth of the damage caused by the wire sawing process.

3.2 The ball/ring on ring test machine

In order to get a wide applicability for different samples dimensions, the testing machine has several rings of different diameters. The force transducer has a capability up to 200 N. The displacement of the ball or the top ring is imposed and both the force and the displacement are recorded. In order to get a quasi-static test, the velocity is very low. In this case, the imposed displacement had a velocity of 5 μm/s. The results of the tests are shown ahead.

3.3 Sets of wafers

Unfortunately only three different set of wafers were available to prepare. All of them have an original thickness of approximately 250 μm. Each group was subjected to caustic soda baths of different duration. Finally, they were cut in four pieces by means of a laser giving four samples for each wafer of 62.5mm x 62.5mm dimensions. The characteristics of each group are shown in table I

Table I: Samples tested

Group	Number of samples	Bath duration (min)	Mean value of thickness (μm)	Mean value of decreased thickness
A	20	3	229.9	10.9 (μm/face)
B	20	6	209.9	20.2 (μm/face)
C	24	9	194.6	28.6 (μm/face)

3.4 Testing wafers and results

Samples of group A were tested with the ring on ring device. The support ring employed had a diameter of 20 mm and the diameter of the top ring was 10 mm. All samples broke correctly and they showed a non-linear behavior due to large displacement and contact between sample and rings. The results are shown in figure 4.

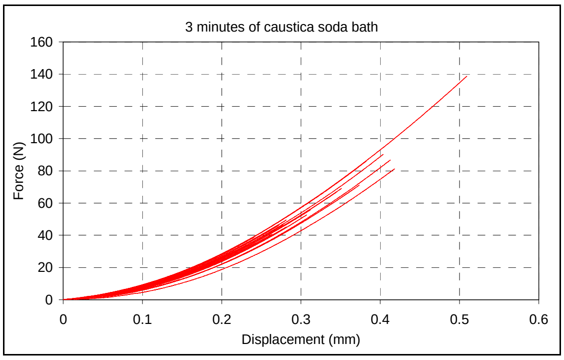

Figure 4: Results of group A

The first attempts to test samples of group B in the ring on ring device reveals that buckling occurs. The buckling (irregular bending of the outer part of the sample [7]) can be observed in figure 5.

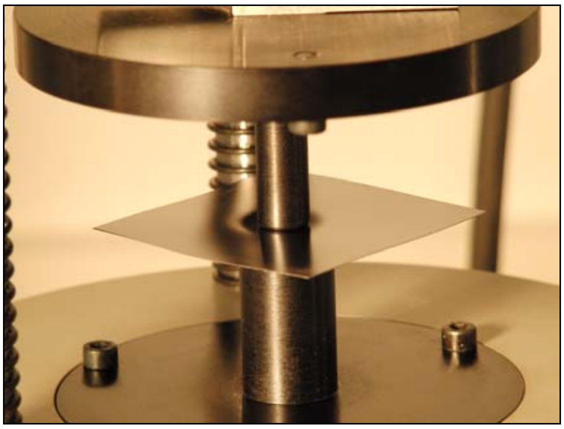

Figure 5: Buckling in one test

For this reason, samples of groups B and C were tested in the ball on ring device. The support ring had a diameter of 10 mm and the ball one of 2 mm. Therefore, results of tests of group B and C cannot be compared directly with results of group A due to the size effect. However, results of groups B and C can be compared between them.

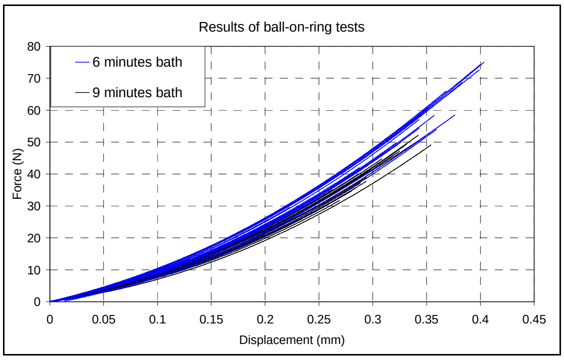

Figure 6: Results of groups B and C

As can be seen in figure 6, the different thicknesses result in different stiffness values of the tested wafers. As in the case of ring on ring test, the samples tested in the ball on ring device showed also a non-linear behavior.

4 ANALYSIS OF THE TEST RESULTS

4.1 Preliminary analysis

In a first step, an analytical method has been employed. The maximum stress at failure moment has been taken from the literature [6]:

For the ring on ring test:

$$\sigma_r = \frac{3F}{4\pi h^2}\left[(1-\nu)\frac{r_2^2 - r_1^2}{r_{eq}^{\ 2}} - 2(1+\nu)\,\mathrm{Ln}\left(\frac{r_1}{r_2}\right)\right] \qquad (1)$$

Where F is the fracture load; h is the thickness; ν is the Poisson coefficient; r_1 is the radius of the inner ring and r_2 of the outer ring; r_{eq} is the equivalent sample radius. For square samples the equivalent radius is:

$$r_{eq} = \frac{\frac{L}{2}\left(1+\sqrt{2}\right)}{2} = 1.207\,\frac{L}{2} \qquad (2)$$

Where L is the side length of the sample.

For the ball on ring test:

$$\sigma_r = \frac{3F(1+\nu)}{4\pi h^2}\left[1 + 2\,\mathrm{Ln}\left(\frac{r_2}{r_1}\right) + \frac{(1-\nu)}{(1+\nu)}\left(1 - \frac{r_1^{\ 2}}{2r_2^{\ 2}}\right)\frac{r_2^2}{r_{eq}^{\ 2}}\right] \qquad (3)$$

The terms are the same as those defined in equation (1).

Using these expressions, the fracture stress has been calculated for each test. For brittle materials the Weibull distribution is commonly used to evaluate statistically the results [2], [3]. The probability of failure is defined as:

$$P_f = 1 - e^{-(\sigma/\sigma_\theta)^m}$$

The parameter σ_θ represents the characteristic fracture stress at which 63.2% of all samples fail. The Weibull module m informs about how scattered the results are. The Weibull fitting of the fracture stresses of the tests is represented in figure 7:

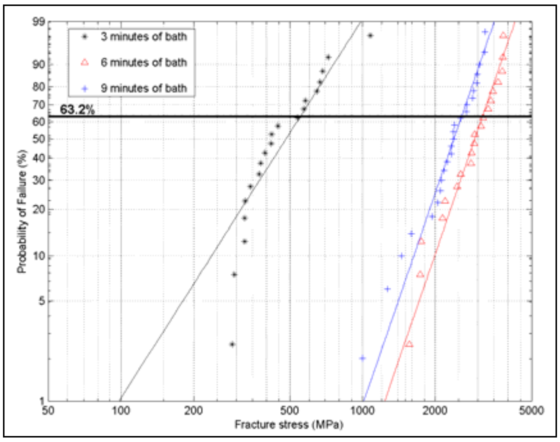

Figure 7: Adjustment to Weibull distribution

It can be seen that for wafers bathed more than 6 minutes, the results are very close. The strength is much higher than for ones which are bathed only 3 minutes. This can be visualized easily in figure 8.

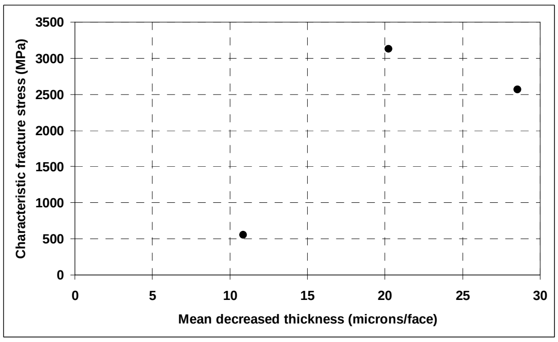

Figure 8: Characteristic fracture stress (σ_θ) versus decreased thickness

This result agrees with the assumption that in center zone of the wafers the cutting damage is lower than near the edges. It can be seen that decreasing more than 20 µm per face doesn't improve the strength of wafers. So, these results obtained in the preliminary analysis may explain the different values of the damaged depth in the literature.

There're some false assumptions in this preliminary study. The most important is that these expressions are valid for linear behavior of samples during the test and this is not the case. Moreover, the size effect hasn't taken into account. However, a first quick analysis may give an idea of the results that we'd expect in a more detailed study.

4.2 FE model

To get a correct interpretation of the test results implies to develop a reliable numerical model. As it's clear in figures 4 and 6, samples showed a non-linear behavior during the test. Therefore, analytical methods may be used to get an idea of the goodness of the results but it can't be considered as the final result of the study.

The Finite Element Method has been employed in this case to analyze the results using the commercial software ANSYS. Wafer and supports have been modeled with shell elements. The anisotropy of the silicon is considered using the following constants:

c11=165.6 GPa
c12=63.9 GPa
c44=79.5 GPa

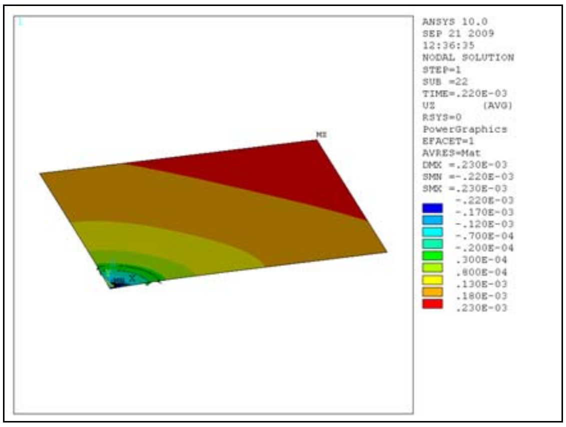

Figure 9: Displacements in the FE model

Nonlinearities due to large deflection and contact between the sample and the ring and ball were taken into account. The coefficient of friction used has a value of 0.35. In figure 9 the displacement in the model can be seen and in figure 10 a zoom of the contact zone is shown.

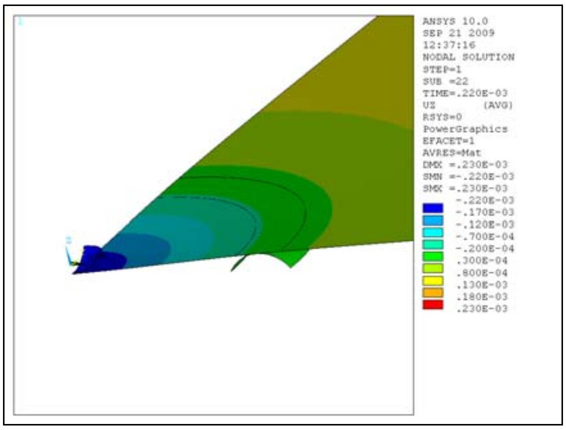

Figure 10: Zoom of the contact zone

However, the adjustment of the model to the test result hasn't been achieved correctly. As can be seen in figure 11, the model behaves more rigid than the test.

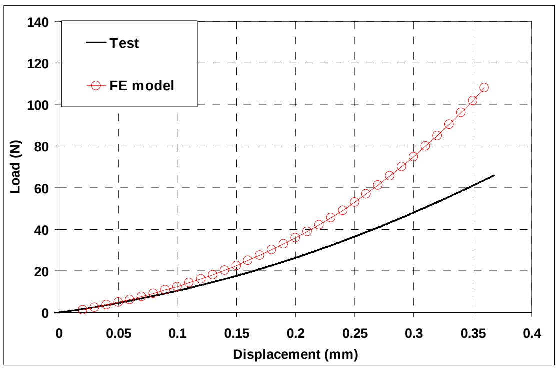

Figure 11: Fitting of the FE model to the test

In the first steps the fitting is quite good. This implies that the linear elastic behavior is achieved correctly. Over 0.1 mm the FE model curve separates of the test one becoming more rigid. Further investigations are being carried out in order to solve this handicap.

5 SUMMARY AND CONCLUSIONS

The damage in wafers caused by the wire sawing process has been evaluated. Previous studies carried out with the four line bending tests showed that removing 30µm per face, the damaged layers of the wafers has been eliminated. It's suspected that the depth of the damage is different in the central zone of the wafer than near the edges. Then, the ball/ring on ring test has been employed to study this hypothesis since the failure is due to cracks far away of the edges.

The tests are described in detail and the results are shown. There were three different groups of samples and one of them was tested with the ring on ring and the other two with the ball on ring test. Then, the correction by size effect is necessary to compare the results.

As a first step analytical methods have been employed in the test results analysis. The failure stress has been obtained for each test using expressions from the literature. Then, they have been fitted to a Weibull distribution and the characteristic fracture stresses of each group have been compared. Results show that decreasing 20 µm per face, the failure stress becomes approximately constant. Expressions employed are valid for linear behavior and, moreover, the size effect has been neglected. But this first analysis may be useful to verify the goodness of the results.

Finally, a Finite Element model is currently developed including nonlinearities. The details of the model are shown and also the first fitting to the test. At this moment, the adjustment is not quite good but further investigations are being carried out to solve it.

The way to study the difference between the damage depth in the central zone or near the edges is explained. Tests are described in detail and the numerical model is presented. A previous analysis with analytical methods gives good results.

6 ACKNOWLEDGEMENTS

This work has been carried out under the sponsorship of the University State Secretary, belonging to Spanish Ministry of Science and Innovation, in its contract TEC2008-06798-C03-03. The presented results have been obtained in cooperation with Institute of Solar Energy (IES) and Microelectronic Technology Institute (TIM).

7 REFERENCES

[1] Barredo et al. *"The influence of different surface treatments on the mechanical strength of silicon wafers"*. 22nd European Photovoltaic Solar Energy Conference, Milan, Italy, 2007

[2] Schoenfelder et al. *"Comparison of test methods for strength characterization of thin solar wafer"*. 22nd European Photovoltaic Solar Energy Conference, Milan, Italy, 2007

[3] Cotterell et al. *"The Strength of the Silicon Die in Flip-Chip Assemblies"*. Journal of electronic packaging, ASME, USA, 2003.

[4] Kao et al. *"Wafer Slicing and Wire Saw Manufacturing Technology"*. Proceedings of the 1997 NSF Design & Manufacturing Grantees Conference, pp. 239-240, 1997

[5] Park et al. *"Correlation between wafer fracture and saw damage introduced during cast silicon cutting"*. 15th Workshop on Crystalline Silicon Solar Cells and Modules: Materials and Processes, Colorado, USA, 2005

[6] Choi et al. *"Slow Crack Growth Behavior and Life/ Reliability Analysis of 96 wt % Alumina at Ambient Temperature with Various Specimen/Loading Configurations"*. NASA/TM, 2000

[7] Coletti et al. *"Mechanical Strength of Silicon Wafers Depending on Wafer Thickness and Surface Treatment"*. 21st European Photovoltaic Solar Energy Conference, Dresden, Germany, 2006