COMPARISON OF TEST METHODS FOR STRENGTH CHARACTERIZATION OF THIN SOLAR WAFER

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ABSTRACT: The Photovoltaic industry still tends towards thinner wafers with larger area leading to higher breakage rate in production processes. Strength characterization is needed in order to understand the fracture process and to optimize process steps. In this work different methods to measure the strength of photovoltaic wafers were presented and performed. Due to large deflection in experiment non-linear numerical methods must be used for strength evaluation. Besides the large influence of thickness variation it was found that the 4-point bending test and the ball-on-ring test are appropriate test methods. In twist test calculating reliable fracture stress values in comparison to the fracture behavior was more difficult. This test method seems to be less suitable for strength characterization.

Keywords: strength, experimental methods, reliability

1 INTRODUCTION

Shortage of solar grade silicon leads to a decrease in wafer thickness resulting in larger wafer deformation and fracture during solar cell manufacturing. Nevertheless the photovoltaic industry will further decrease the wafer thickness and increase the wafer area. Therefore the behavior of strength and the mechanism of breakage have to be understood in order to minimize the fracture rate and to optimize the process steps. Until today there are no standardized test conditions to measure the strength of thin silicon wafers.

There are various test methods for characterizing the strength of brittle materials like silicon wafers. In the photovoltaic industry the twist test is often used and discussed [1, 2]. This test method was introduced in the early 80s as strength test in photovoltaic industries [3]. Other test methods like uniaxial and biaxial bending tests, which are well known from general material testing, are also applicable to silicon wafers. Uniaxial bending tests like the 3-point or 4-point bending [4] tests mainly load the sample surface and edges. Biaxial bending test like ring-on-ring [5], ball-on-ring [6] test or the piston-on-3-balls [7] test leading to a biaxial stress field at the sample surface. Therefore edge defects are excluded in these tests. If the strength of samples has to be characterized not every test method is suitable to characterize the strength behavior. It depends on the sample geometry, processing steps and the aim of the investigation.

In this work three different methods of strength measurement; (a) 4-point bending test, (b) ball-on-ring test and (c) twist-test were performed and compared.

2 EXPERIMENTS

2.1 SAMPLES

In this investigation monocrystalline (100) pseudosquare silicon wafers from PV industry were used, which were isotextured. The (156x156) mm² wafers have round corners with a diagonal diameter of 195mm. The thickness was measured by weight for every sample. The mean thickness is 176µm for all tested wafers with an absolute variation of thickness between 137µm and 209µm.

For ball-on-ring tests smaller samples were prepared in order to avoid buckling during the test. Therefore samples were broken to (16x16) mm² square samples.

2.2 TEST METHODS

In order to characterize the sample edge and sample surface the 4-point bending test was applied (Fig. 1a). In this test setup the support and loading devices are long cylindrical bars resulting in line contacts on the sample. For the used samples the inner and outer load span was defined to b=55mm and l=110mm, respectively. The cylindrical bars had a diameter of 10mm.

The ball-on-ring test (Fig. 1b) was chosen to characterize the strength behavior of the surface of the samples. In this test setup square samples are placed on a ring and were loaded with a ball. In this work the ring had a diameter of 9.1mm and the ball a diameter of 2mm. In contrast to the 4-point bending only the surface is characterized with this test method. The stress at the edges can be usually neglected and does not cause fracture of the sample.

As third test method the twist test was applied (Fig.1c). In this test the sample is supported by two balls in one diagonal of the wafer and loaded by two other balls in the other diagonal of the wafer. The supporting and loading distance was chosen to b=120mm and the diameter of the balls to 9mm, respectively. The sample will be twisted in this test setup. This results in a stress distribution which is loading the surface and edges in the sample inhomogeneously [1].

For every single test method 50 samples were loaded until fracture occurred. As a result the fracture forces as well as the force-deflection charts were obtained. Latter
are used to compare the experimental and theoretical results. Further experimental parameters are summarized in Tab. 1 for every test.

**Tab. 1: Experimental parameter**

<table>
<thead>
<tr>
<th>Test method</th>
<th>Testing machine</th>
<th>Test rate [µm/s]</th>
<th>Initial load [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-point bending</td>
<td>Zwick(^1)</td>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td>Ball-on-ring</td>
<td>Zwick(^1)</td>
<td>5</td>
<td>0.1</td>
</tr>
<tr>
<td>Twist test</td>
<td>GP STAB-TEST Pro</td>
<td>800</td>
<td>0.25</td>
</tr>
</tbody>
</table>

\(^1\)Zwick universal testing machine 1445

**2.3 RESULTS**

In Fig. 2 the force-deflection charts for every test method are shown. The slope of the curves are scattering in a wide range due to the strong variation in sample thickness. Therefore the fracture forces do not represent the strength behavior because the same fracture force would result in different fracture stress for different sample thicknesses. In Tab. 2 the mean values and standard deviations of fracture forces and deflection are presented. The 4-point bending test shows the highest fracture force. The deflections of the 4-point bending test and twist test are much larger than the sample thicknesses which indicate geometric nonlinear behavior. For the ball-on-ring test the deflection is rather small and linear theory can be used in evaluation.

**Tab. 2: Mean value and standard deviation of fracture forces and deflection**

<table>
<thead>
<tr>
<th>Test method</th>
<th>Fracture force [N]</th>
<th>Fracture deflection [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>STDV</td>
</tr>
<tr>
<td>4-point bending</td>
<td>17.21</td>
<td>2.77</td>
</tr>
<tr>
<td>Ball-on-ring</td>
<td>5.21</td>
<td>0.87</td>
</tr>
<tr>
<td>Twist test</td>
<td>4.71</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Some samples were investigated in order to find the fracture origin and understand the mechanism of fracture in these test methods. In Fig. 3 the principal fracture patterns are shown, which were found on most samples. In the case of 4-point bending and twist test the crack propagates along the diagonal of the wafer. The diagonal is the <110> direction of the crystal and the fracture occurs in the [111] plane being the weakest plane in the silicon crystal. In ball-on-ring test the cracks can also be found in the [111] plane in the <110> direction. In the fracture pattern the crack direction is rotated at 45° because of sample preparation. The fracture origin can be found at the surface in ball-on-ring test. For the 4-point bending test both surface and edges are possible starting points for collapse. In twist test the fracture origin can be assumed at the corners of the sample. But also here the loading balls can cause failure.

**3 EVALUATION OF EXPERIMENTAL RESULTS**

**3.1 CALCULATING FRACTURE STRESS**

The experimental force-deflection curves showed very large deflection for 4-point bending and twist test. Up to 20mm were observed which is caused by the small thickness of the samples (Fig. 2). As a result linear analytical theory, being based on small deflection for calculating the fracture stress is not valid. Therefore the deformation and the stress distributions were calculated numerically with the help of the finite element method (FEM). In this analysis ANSYS were used as FEM code. Nonlinearities like contact problems and large deflection as well as anisotropic material behavior are considered in the FE models. For silicon the following elastic constants were used:

\[c_{11}=165.8 \text{ GPa}\]
\[c_{12}=63.9 \text{ GPa}\]
\[c_{44}=79.6 \text{ GPa}\]

For every test method a separate model was built. In case of 4-point bending and twist test the samples were modeled with shell elements due to the very small thickness in comparison to the other geometric parameters. On one hand the test setup was modeled as rigid contact to consider sliding of the sample. On the other hand the deformation was calculated with respect to the large deformation occurring in the experiments. Because of the large deflection the samples were sliding

**Fig. 2:** Force-deflection charts of experiment and finite element simulation; (a) 4-point bending test, (b) ball-on-ring test, (c) twist test

**Fig. 3:** Fracture pattern of different test methods: (a) 4-point bending test, (b) ball-on-ring test, (c) twist test

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on the supports and friction could not be neglected in the contact regions. However, the coefficient of friction is mostly unknown for the present contact material. Therefore, the coefficient of friction was found empirically by changing it in the FE model until the calculated and experimental force-displacement chart showed good match. For the isotextured wafer a coefficient of friction of 0.5 (twist test) and 0.8 (4-point bending) were used. These large values can be explained by the high roughness of the sample surface. The difference of values is caused by different contact material pairs in 4-point bending and twist test.

For the ball-on-ring test a solid element model was used. In this model the deflection and the stress was calculated with linear theory because of the small deflection in the experiment. Furthermore, the anisotropic material behavior of silicon and the rectangular geometry of the sample were considered in comparison to analytical formulas of the isotropic plate theory.

The relation between fracture force and fracture stress can be read from the FE analysis. The relation, mostly non-linear, has to be calculated for the different thicknesses of the samples. To reduce numerical calculations the force-stress charts were calculated only for few thicknesses within the tested range. The solutions for the other thicknesses were interpolated based upon the calculated results.

3.2 STATISTICAL EVALUATION

When the fracture stress is calculated for every sample, the results have to be evaluated statistically. For brittle materials like silicon the Weibull distribution \[8\] is mostly used to characterize the strength. This distribution is based on the weakest link theory which represents the failure mechanism of brittle structures. The probability of failure is defined as:

\[
P = 1 - \exp\left(\frac{\sigma}{\sigma_0}\right)^m\]

In this equation the parameter \(\sigma_0\) represents the characteristic fracture stress at which 63.2% of all samples fail. The Weibull modulus \(m\) gives information about the scattering of the samples. A high value of \(m\) means a small variation in strength and vice versa. In this work the parameters were estimated with the maximum likelihood method. The confidence bounds were calculated with the tables in \([9, 10]\).

4 RESULTS

In Fig. 2 the force-deflection charts calculated with the FE models are shown in comparison to the experimental curves. The results from numerical calculation are presented for minimal and maximal thickness in test. 4-point bending test and twist test show very good agreement after adjusting the coefficient of friction for every test setup. The large variation in experimental curves is caused by the thickness variation of the samples. This can also be seen in the numerical results. For ball-on-ring test the FE model shows a stiffer force-deflection behavior. This can be explained by additional deflection of the support in experiment in the range of a few micrometers. In Fig. 4 the deformation of the samples in the FE models is shown.

After calculation of force-deflection charts the fracture stress was obtained from the FE models. In comparison to the fracture analysis (Fig. 3), the fracture stresses were calculated at the assumed fracture origins. For the ball-on-ring test the maximum stress occurred at the bottom surface opposite the loading ball, where the fracture origin is located. In 4-point bending test the edge shows the highest stress value, which can also be assumed as starting point of failure. The twist test shows the highest stress at the surface under the supporting and loading balls. But fracture analysis leads to the assumption that fracture occurs mostly in the corners of the wafer and not at the surface. Therefore not the maximum stress in the sample but rather the maximum stress at the corner was calculated as fracture stress. The characteristic fracture stress and Weibull modulus of all test methods is shown in Tab. 3. In Fig. 5 the probability plots are presented.

<table>
<thead>
<tr>
<th>Test method</th>
<th>Characteristic fracture stress (\sigma_0) [MPa]</th>
<th>Weibull modulus (m) [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-point bending</td>
<td>262 (255…269)</td>
<td>9 (7.3…10.5)</td>
</tr>
<tr>
<td>Ball-on-ring</td>
<td>372 (365…380)</td>
<td>12 (9.8…14.1)</td>
</tr>
<tr>
<td>Twist test</td>
<td>157 (153…162)</td>
<td>8.4 (6.8…9.9)</td>
</tr>
</tbody>
</table>

The ball-on-ring test shows the highest characteristic stress value for the sample surface. The 4-point bending shows a high strength as well. But it is influenced by the edge defects. The strength in twist test is dominated by the failure in the corner of the sample resulting in small
fracture stress. The smallest scattering of strength is represented by the ball-on-ring test. The 4-point bending and twist test have nearly the same Weibull modulus.

Fig. 5: Probability plots for all test methods

It can be seen from Fig. 5 that stress values of 4-point bending test are in the same region as for ball-on-ring test. That means fracture at the surface is also possible in the 4-point bending test. In contrast all stress values of the twist test are below the minimum value of the ball-on-ring test. Therefore fracture at the surface is unlikely to expect in the twist test. It has to kept in mind that these results are based on the assumption of fracture mechanism (Fig. 3).

5 DISCUSSION

For comparison of the different test methods the $1^{st}$ principal stress is plotted along the maximum loaded regions in Fig. 6. In 4-point bending test the stress is nearly constant until the edge. Due to the larger deflection of the edge the stress is slightly increased. In ball-on-ring test the maximum of stress occurs in the center of the sample and strongly decreases toward the wafer edge. In twist test the stress distribution is more inhomogeneous along the diagonal with stress maximum at the loading or support balls. The stress varies relatively strong along the path coordinate.

The small thickness of silicon wafers leads to large deflection in experiment. Nevertheless the strength behavior can be characterized with the help of numerical methods. However the concept of the test methods can be change drastically. In 4-point bending test the region of constant stress between the inner load span is vanished and the stress value depends on the coordinate like in 3-point bending test. In ball-on-ring test stability problems like buckling have to be considered for very thin samples. This can be avoided by preparing smaller samples [11]. However this is only applicable if only the sample surface should be characterized. The twist test changed the loading condition which is caused by the large deflection. The bending moment and deflection dominate in one diagonal direction which is caused by imperfections in the experiment. Then the deformed shape is similar to uniaxial bending. However the supporting and loading balls lead to locally high stress at the sample surface that has to be investigated in more detail. Furthermore in twist test tensile stress occurs on both sample sides. This inhomogeneous stress distribution can result in problems in strength evaluation if the fracture origin is uncertain.

Another aspect by strength characterization is the dependence of fracture stress on the loaded volume or area also known as size effect. It means that the fracture stress is decreasing with increasing volume or area of the sample. In the different test methods the effective loaded area is varying. Even the sample size is different for the ball-on-ring test. However, considering the size effect for non-linear behavior, it is much more complicated than in linear cases and should be investigated in more detail. In this work it is assumed that the size effect has only a small influence on the presented results and is neglected in further discussion.

In this investigation is shown that different test methods characterizing different strength behavior. While in the 4-point bending test the sample surface and sample edge is tested, the ball-on-ring test characterizes only the surface. Both tests can also be used in combination to analyze the whole wafer. In the twist test also the sample corner is tested besides surface and edge. To avoid difficulties in stress evaluation the 3-point bending test can be used as an alternative test method for the corner regions.

If fracture forces and fracture stresses (Tab. 2 and 3) are compared, the difference of these parameters becomes obvious. The fracture stress describing the fracture behavior of the samples can be compared to each other. However the fracture forces are experimental values, which strongly depend on the geometry of the samples and the test setup. A higher fracture force does not mean higher fracture strength in all cases. But stress evaluation with respect to non-linear effects can always be used as reliable strength characterization. Additionally it is important to consider geometric variations, e.g. the thickness of silicon wafer, to determine accurate stress values.
6 CONCLUSIONS

This investigation has shown that the test method has a strong influence on the derived results. Nonlinearities in the experiment caused by the small thickness must be considered in strength evaluation. In 4-point bending and ball-on-ring test the stress distribution is well defined and can be correlated to the fracture origin. In contrast the stress distribution is inhomogeneous in twist test. Furthermore the relation between fracture origin and fracture stress was hard to find for this test method.

The thickness must be measured for photovoltaic wafer for every single sample because of the large variation in thickness. The calculated fracture stress is strongly influenced by the sample thickness. Furthermore it was shown, that in contrast to force only stress can be used to characterize the strength of samples.

The size effect of strength for different test methods should be considered in strength investigations. Due to the nonlinearities in experiment the calculation of the size effect is much more complicated than in linear cases. Further investigations are needed to understand the influence of the size effect in non-linear cases in order to obtain reliable strength parameters.

7 ACKNOWLEDGEMENT

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8 REFERENCES

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