Comprehensive analysis of strength and reliability of silicon wafers and solar cells regarding their manufacturing processes

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ABSTRACT

The mechanical strength of monocrystalline and multicrystalline silicon wafers is mainly dictated by the cracks induced during the wire-sawing process. Different sawing technologies, such as diamond-wire- or slurry-based processes, lead to different strength behaviours of as-cut wafers. Furthermore, the strength is strongly influenced by texturization, and at this stage can be interpreted as the basic strength of a solar cell. The metallization and firing processes determine the final strength and reliability of a solar cell, with the metallization contacts being the root cause of breakage of solar cells, depending on the particular cell concept. This paper gives a comprehensive overview of the typical ranges of strength for as-cut wafers, textured wafers and solar cells, for the two different sawing technologies. Around 100 batches with 4,253 samples were evaluated in the study.

Introduction

Diamond-wire-sawn wafers have been receiving more attention during the last few years because of the potential for higher cutting speeds, less wire consumption and the use of cheaper cooling fluids, in comparison to the standard slurry process [1]. Diamond-wire sawing is expected to gain market share at the expense of slurry-based wafering over the next 10 years [2]. As well as the challenges in cutting and texturization for multicrystalline wafers, the comparatively low strength of diamond-sawn wafers is perhaps the most critical aspect in the solar cell production process. Because the wafer makes up 33% of the overall module cost [2], this strength is very important in order to ensure small breakage rates. The questions therefore arise as to how the strength changes within the solar cell production processes, and what the differences are between diamond-sawn and standard slurry-sawn wafers.

The strength of silicon solar cells is defined by defects on the silicon surface, depending on the manufacturing of the wafers and cells [3]. For as-cut wafers, the related defects are mainly cracks induced by the sawing process [4]. Besides the type of material used (multicrystalline or monocrystalline silicon), the major factor affecting wafer strength is the sawing technology, which leads to different cracks, and therefore to different strength behaviours. In the processes at the start of cell production, the wafer surface is then altered again by saw-damage removal and texturization processes.

"Besides the type of material used, the major factor affecting wafer strength is the sawing technology."

This paper reports on the strength behaviour of diamond- and slurry-sawn wafers and gives a comprehensive overview of the typical ranges of strength values for as-cut wafers, textured wafers and solar cells. In the study 2,207 as-cut wafers, 743 textured wafers and 1,303 solar cell samples were tested and evaluated at Fraunhofer CSP.

Methods for testing strength

The failure of wafers and solar cells arises when critical loading is reached, which is defined by the most critical defect, according to the weakest link theory for brittle materials [5]. With the use of fractography techniques, fracture origins for slurry- or diamond-sawn wafers and solar cells were found on the surface, as shown in Fig. 1; this correlates with the assumption that the sawing process induces the dominant damage on the wafer surface. The kinds of defect, however, vary between slurry and diamond-wire sawing: cracks of different shapes and depths occur on the surface, which govern the strength of the wafer. With solar cells, the fracture origin for the back side is mostly found in the overlapping region of the different metallization pastes.

Although there are different optical methods for detecting cracks in the millimetre range that have been induced on the wafer surface after the sawing process [6], there is still no reliable industrial method for characterizing the cracks that define the as-cut wafer strength, which are in the tens of micrometres range [7]. Because of this fact, fracture tests are the only way to determine the strength of as-cut/textured wafers and solar cells.

Fig. 2 shows the most frequently used fracture test methods, categorized by uniaxial and biaxial testing [8]. The uniaxial fracture tests are used for evaluating edge and surface defects on small or large samples. The four-point bending (4PB) is preferred over the three-point bending (3PB) method, because of the larger constantly loaded area between the upper two rollers with 4PB, instead of just one line under the upper roller in the case of 3PB. The 3PB can be used for very small samples or as a method for finding the fracture origin (see Klute et al. [7]).

The biaxial fracture tests are mainly used for the evaluation of surface strength of small samples if the edge defects need to be suppressed, such as for laser-cut specimens. In general, the ring-on-ring test should be preferred over the ball-on-ring test, since the loaded area is larger. However, because of the small thickness of photovoltaic wafers, the ring-on-ring test is limited to small ring geometries, as otherwise the stress field would become highly nonlinear [9]; for this reason, the ball-on-ring test is mostly used for thin semiconductor materials.

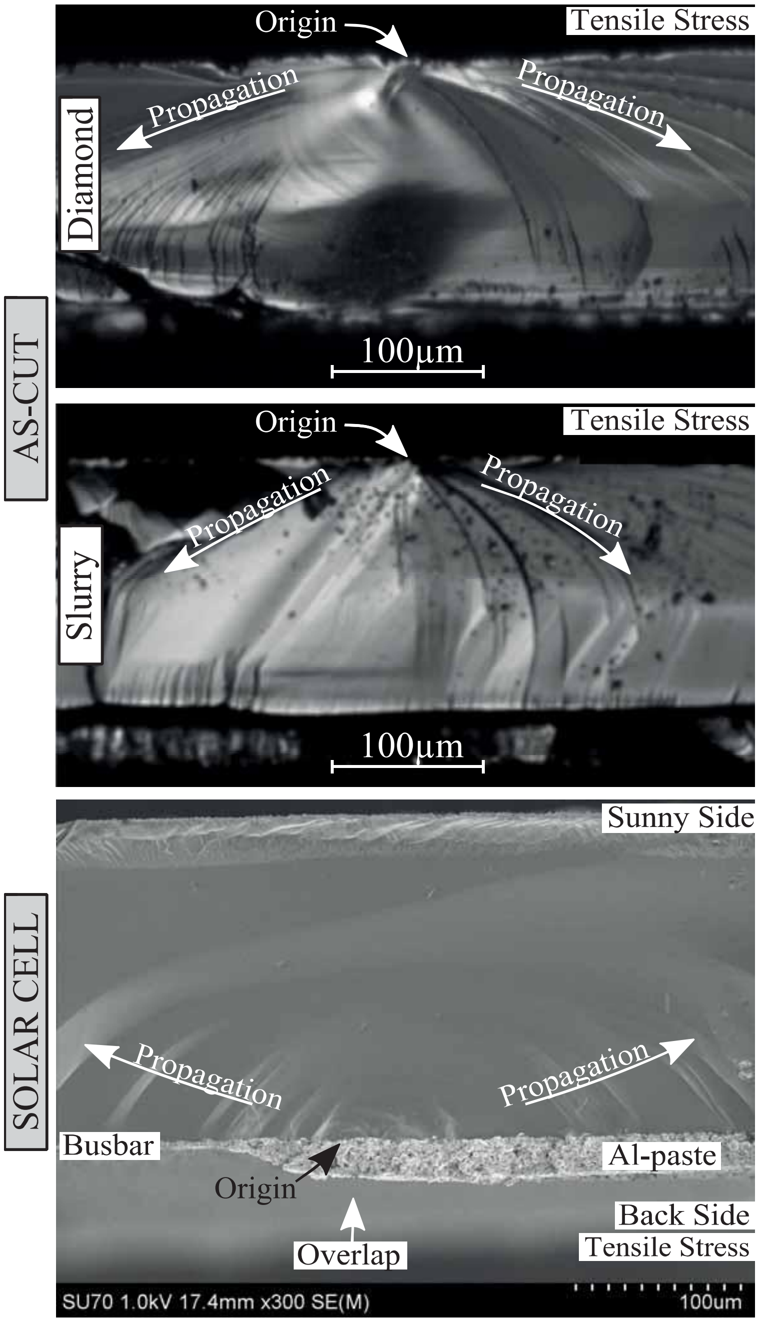

Figure 1. Fracture origins from optical and scanning electron microscopy (SEM) at the surface of diamond- and slurry-sawn monocrystalline wafers and of solar cells from samples after a four-point bending (4PB) test (a cross-sectional view of the fracture surface is shown).

For an evaluation and comparison of the biaxial and uniaxial tests, a numerical model is required in order to accurately calculate the fracture stresses and effective size. In this paper only the results from 4PB are used, because the area evaluated is the largest, and edge defects are considered.

Statistical evaluation and size effect on strength

After the tests were performed, it was necessary to calculate the fracture stresses using finite element models, which consider nonlinearities as large deflections and contacts between sample and rollers [3]. These stresses were then evaluated statistically using a two-parameter Weibull distribution [5,10]:

$$P = 1 - \exp\left[-\left(\frac{\sigma}{\sigma_\theta}\right)^m\right] \quad (1)$$

where σ is the loading, σ_θ is the characteristic fracture stress at which 63.2% of all samples fail, and m is the Weibull modulus, which represents the scattering of the fracture stresses. A high Weibull modulus represents a small variation and vice versa.

In fracture tests of brittle materials another important fact is the effect of size on strength [5,8]: the measured strength depends on the sample area or volume. With increasing volume, there is a greater likelihood of finding a critical defect in this volume, which results in a smaller fracture stress. Different sample sizes and load cases therefore mean that results from uniaxial and biaxial fracture tests cannot be directly compared. Thus, because of the effect of size on strength, the size of the samples or loaded geometry needs to be taken into consideration.

If surface-related breakage is assumed, the area of the wafer needs to be analysed; an effective area A_{eff} is therefore calculated for the different samples and test geometries. This effective area is influenced by the sample size, test parameters and Weibull modulus. For an effective area A_{eff}, the size-independent scale parameter σ_θ can be determined from the equation:

$$\sigma_0 = \sigma_\theta {A_{eff}}^{1/m} \quad (2)$$

Fig. 3 shows the relationships between the effective area, Weibull modulus, characteristic fracture stress and test geometry for two different 4PB configurations. The effective area for the 4PB configuration can be calculated by:

$$A_{eff,4PB} = b\frac{m\,l_1 + l_2}{1+m} \text{ for } t \ll b \quad (3)$$

where b and t are the length and thickness of the sample, and l_1 and l_2 are the spans of the inner and outer rollers. It can be seen that different test configurations can lead to different results in experimentally measured characteristic fracture stresses.

For the study reported in this paper all characteristic fracture stresses from different sample sizes and test configurations were converted to an effective area of 9,116mm^2, which represents a 4PB with standard test conditions (l_1 = 55mm, l_2 = 110mm), a wafer size of 156mm × 156mm and a Weibull modulus of m = 15.

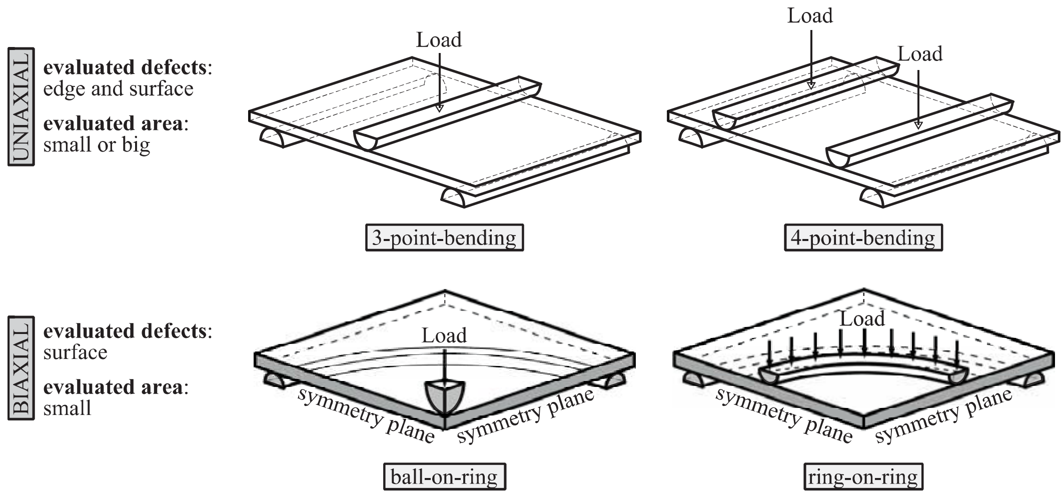

Figure 2. Different fracture test methods for determining the strength of as-cut/textured wafers and solar cells.

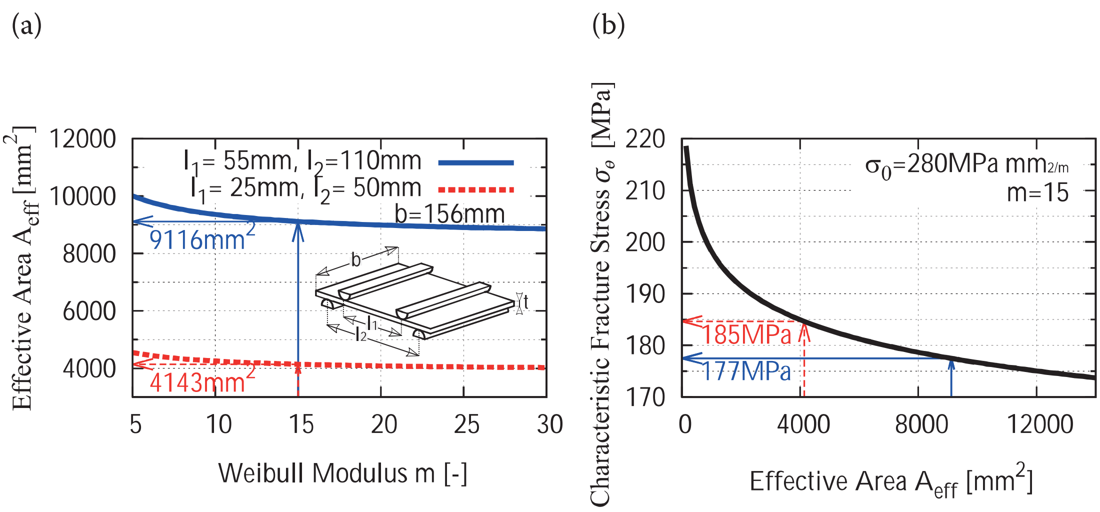

Figure 3. (a) Dependence of the effective area A_{eff} on the Weibull modulus m. (b) Influence of the effective area on the characteristic fracture stress σ_θ.

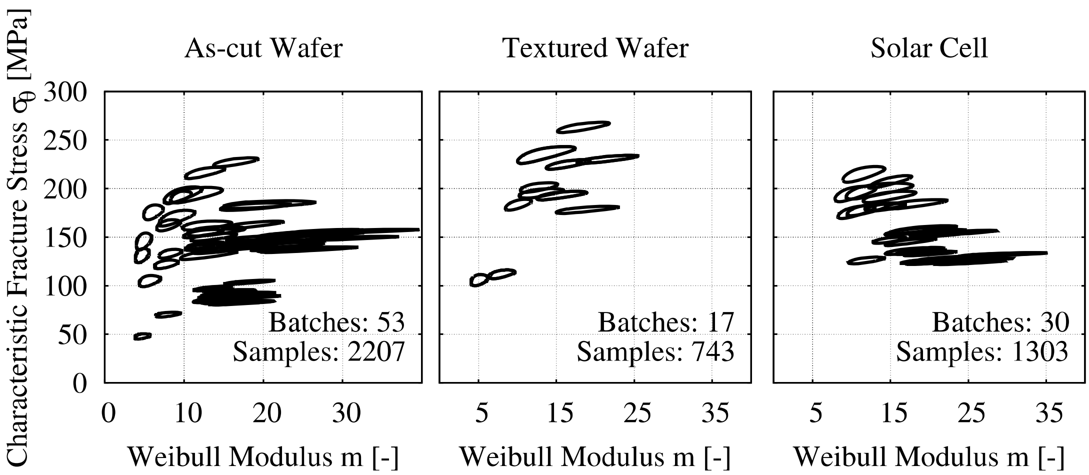

Figure 4. Strength results for as-cut/textured wafers and solar cells, tested in 4PB at Fraunhofer CSP, each ring (MLE 90% confidence ring) representing one strength test with an average of 42 wafers per test.

Overview of typical ranges of strength

Although the strength of silicon wafers is influenced by many parameters of the sawing process, the intention of this paper is to give an overview of the typical strength-range results. The data obtained from strength testing over the past few years, with 100 batches and over 4,250 samples tested in 4PB at Fraunhofer CSP, is used (see Fig. 4).

Because of the effect of size on strength, all data from 4PB experiments with as-cut wafers were converted to an effective area of A_{eff} = 9,116mm^2 and then sorted by material, sawing process and loading direction. An overview of parallel and perpendicular loadings to the saw marks is shown in Fig. 5. The boxes represent the outer limits of the Weibull parameters based on the experimental data, considering the limits of the confidence bounds; the values are shown in Table 1. In general, for every material and sawing technology, lower strength is demonstrated with parallel loading than with perpendicular loading, but the difference between diamond-sawn wafers and slurry-sawn wafers is greater in the former.

Material

In initial results multicrystalline diamond-sawn wafers demonstrate lower strength than monocrystalline ones. In the case of slurry-sawn wafers, however, the strength range for multicrystalline wafers is similar to that of monocrystalline wafers, although the monocrystalline wafers exhibit less variation in strength. Monocrystalline wafers tend to a higher Weibull modulus than multicrystalline ones; they also have a lower scattering in fracture stress, except for monocrystalline diamond-sawn wafers under perpendicular loading.

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For analysing the strength of quasi-mono slurry-sawn wafers, only a few data points in parallel loading were acquired, but they seem to fit within the range between monocrystalline and multicrystalline wafers.

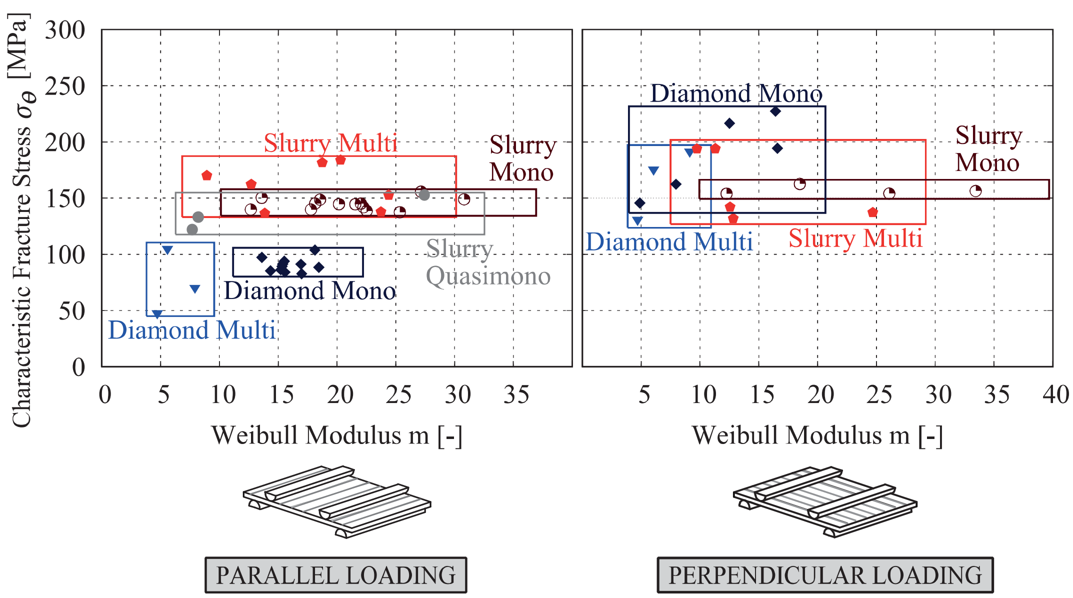

Figure 5. Overview of typical ranges of strength for as-cut wafers tested in 4PB (A_{eff} = 9,116mm^2) for different sawing technologies and material types with loading parallel and perpendicular to the saw marks.

Sawing technology	Material	Loading	Weibull modulus *m*	Characteristic fracture stress σ_θ [MPa]
Slurry	Mono	Parallel	10–37	134–158
		Perpendicular	10–40	149–166
	Multi	Parallel	7–30	133–187
		Perpendicular	8–29	127–202
Diamond	Mono	Parallel	11–22	80–106
		Perpendicular	4–21	137–232
	Multi	Parallel	4–10	45–111
		Perpendicular	4–11	124–197

Table 1. Overview of typical ranges of strength for as-cut wafers tested in 4PB (A_{eff} = 9,116mm^2) for different sawing technologies and material types, with parallel and perpendicular loading to the saw marks.

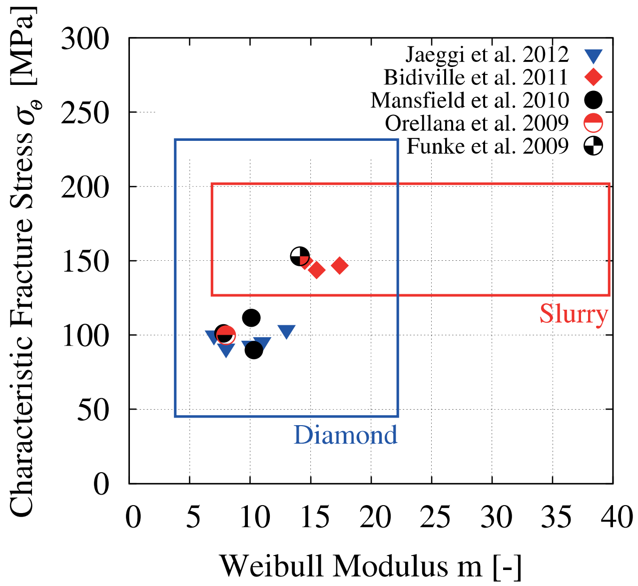

Figure 6. Overview of the typical ranges instrength of diamond- and slurry-sawn wafers (material and both types of loading combined), compared with strength values given in the literature [11–15].

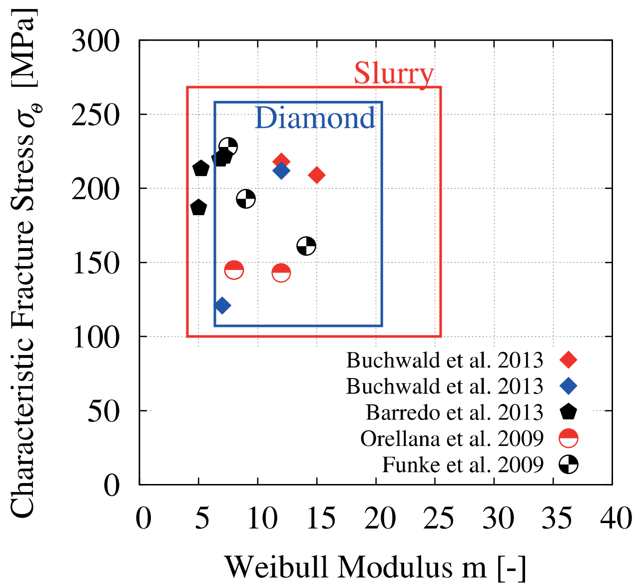

Figure 7. Overview of the typical ranges in strength of diamond- and slurry-sawn wafers after texturization (material and loading combined), compared with strength values given in the literature [11,12,16,17].

Sawing technology

The sawing process itself introduces strength-limiting cracks in the wafer surface; thus the wafer strength heavily depends on the sawing technology. Compared with slurry-sawn wafers, the strength of diamond-sawn wafers is always lower in a parallel-loading configuration, and in the same range, or higher, with perpendicular loading. It can also be observed that the slurry-sawn wafers tend to higher Weibull moduli (less scattering) than in the case of diamond-wire-sawn wafers.

In Fig. 6 the strength results for different materials and loadings have been combined and are compared with values from the literature [11–15]. The red and blue dots indicate slurry- and diamond-sawn wafers respectively, while the black dots show strength values for an unknown sawing technology. Apart from Orellana et al. [12], the literature values fit within the ranges presented. The tendency for higher characteristic fracture stresses and Weibull moduli in the case of slurry-sawn wafers can also be observed from the values in the figure.

Effect of etching and solar cell process

During the initial cell processing steps for the solar cell (saw-damage etch and texturization), the wafer surface is altered and the strength behaviour is affected. In Fig. 7 the strengths of textured wafers for different materials and loadings are combined and compared with values in the literature values [11,12,16,17]. The red and blue dots indicate slurry- and diamond-sawn wafers respectively, while the black dots show the strength values for an unknown sawing technology. It can be seen that the strength of textured diamond-sawn wafers is within the range as for slurry-sawn wafers; however, the strength limit of slurry-sawn wafers is higher than that of diamond-sawn wafers for current etching procedures.

The typical strength range for as-cut/textured wafers and solar cells with the most critical loading is shown in Fig. 8. For as-cut or textured wafers, critical loading is when the rollers are parallel to the saw marks; in the case of solar cells, the most critical loading means that the back side is in tension and the rollers are perpendicular to the busbars [3]. In addition, the data from monocrystalline and multicrystalline samples were grouped together in the analysis. Several different solar cells concepts – such as aluminium back-surface field (Al-BSF), passivated emitter rear cell (PERC) and interdigitated back contact (IBC) – were also evaluated. Typical strength-range values are given in Table 2.

For both diamond-wire- and slurry-sawn wafers, the strength is significantly increased as a result of the texturization process, but slurry-sawn wafers are still stronger than diamond-wire-sawn ones. After the solar cell processing, the strength decreases again for all tested solar cells, independent of the sawing technology. The critical area for cells is the back side with small- or large-area metallization and where the metallization overlaps. It can therefore be assumed that the metallization changes the silicon surface and the defects, and induces new defects or residual stresses for all tested types of solar cell [3,18]. The front side of a solar cell is stronger, and the strength is governed by the textured surface, with influences from the small areas of metallization. This means that, by focusing on the mechanically weakest region, no differences in slurry-sawn or diamond-sawn wafers can be observed after solar cell processing.

Fig. 9 shows the mean values from all experiments for the Weibull

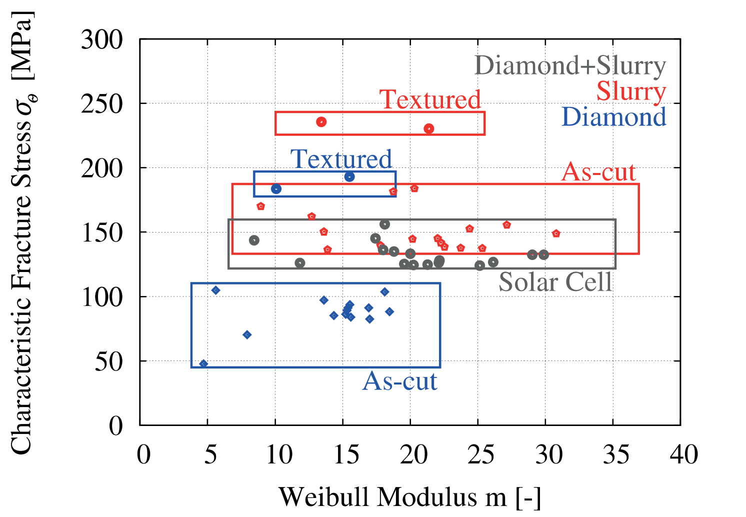

Figure 8. Overview of typical strength ranges for as-cut/textured wafers and solar cells tested in 4PB (A_{eff} = 9,116mm^2). The data are based on the most critical loading (parallel to saw marks for wafers, perpendicular to busbars for solar cells).

parameters and a predicted probability of breakage for a loading of σ = 70MPa. The Weibull modulus (Fig. 9(a)) decreases slightly after texturization (fracture stresses increases), and increases again after the final solar cell production steps. Texturization increases the characteristic fracture stress (Fig. 9(b)) by 53% for slurry-sawn wafers and 116% for diamond-sawn ones; this effect of higher strength with higher scattering after texturization is commonly known for increasing surface strength [19].

After most of the surface damage has been eliminated, the defects are smaller and fracture stresses increase; consequently, comparatively larger defects can be easily induced, causing lower fracture stresses and overall a higher scattering of strength. Before texturization the characteristic fracture stress of slurry-sawn wafers is 75% higher than that of diamond-

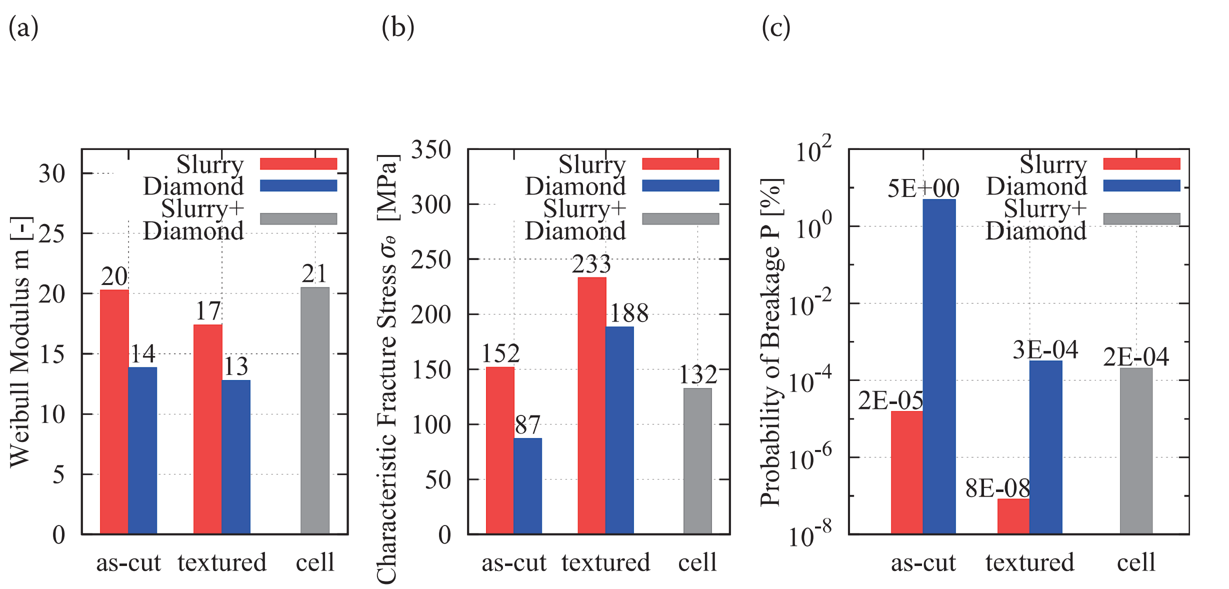

Figure 9. Changes occurring during solar cell production for slurry- and diamond-sawn wafers, for a loading of σ = 70MPa and A_{eff} = 9,116mm^2: (a) Weibull modulus *m*; (b) characteristic fracture stress σ_θ; (c) probability of failure *P*.

Sawing technology	Material	Loading	Weibull modulus *m*	Characteristic fracture stress σ_Θ [MPa]
Textured wafers				
Slurry	Mono+multi	Parallel	10–25	226–243
Diamond	Mono+multi	Parallel	8–19	178–197
Solar cells				
Slurry + diamond	Mono+multi	Back-side tension, busbars perpendicular to rollers	7–35	122–160

Table 2. Overview of the typical ranges of strength for as-cut/textured wafers and solar cells tested in 4PB (A_{eff} = 9,116mm^2). The data are based on the most critical loading (parallel to saw marks for wafers, perpendicular to busbars for solar cells).

sawn wafers; after texturization it is still 24% higher. After the final step of cell production is completed, the characteristic fracture stress decreases by 43% and 30% for slurry-sawn and diamond-sawn wafers respectively.

> "The smallest risk of breakage is demonstrated by textured slurry-sawn wafers."

Using the statistical Weibull parameters one can predict the probability of failure – in other words, the systematic breakage rate of wafers and cells [20]. The breakage rate depends on the load and the loading area; here, it is assumed that the full wafer is stressed by 70MPa. The resulting failure probabilities are shown in Fig. 9(c). For the given load example, the diamond-wire-sawn wafers show the highest breakage rate of around 5%. As-cut slurry-sawn wafers and solar cells are in the lower range of breakage probability, at less than 0.001%. The smallest risk of breakage is demonstrated by textured slurry-sawn wafers; these are the strongest wafers within the cell process.

Conclusions

Strength is an important parameter of not only the wafer substrates but also the solar cells: it governs the reliability or breakage rate in the process and in photovoltaic modules. The strength changes, however, as the wafer progresses to cell manufacturing, mainly because of the wafering, texturization and metallization processes. This paper has given a comprehensive overview of the mechanical strength behaviour of diamond-sawn and slurry-sawn as-cut/textured wafers and solar cells in 4PB tests.

For slurry- and diamond-sawn wafers the fracture origin is always found at the wafer surface; surface defects are therefore strength-limiting defects. For as-cut wafers, it was observed that, except for monocrystalline diamond-sawn wafers in the case of loading perpendicular to the saw marks, the scattering of strength is higher for multicrystalline wafers than for monocrystalline ones. Diamond-wire sawing is a promising technology, with several advantages over standard slurry sawing. A limiting factor for diamond-sawn wafers, however, is still the smaller strength values than in the case of slurry-sawn wafers. For critical loading with the rollers parallel to the saw marks, the strength for slurry-sawn wafers before texturization is 75% higher than for diamond-sawn wafers, and it is still 24% higher after texturization. The wafering process itself and subsequent process steps therefore influence each other and need to be optimized with respect to surface damage and wafer strength.

In the case of solar cells, the back-side metallization dominates the strength, because crack origins can be found near the busbars at overlapping regions between the aluminium and silver paste. The metallization process changes the surface of the silicon and induces new defects, which lead to values of strength below the texturization strength of diamond- or slurry-sawn wafers. Thus, the difference in strength based on the wire-sawing process vanishes, but only when attention is focused on the weakest area in the solar cell. In summary, in order to achieve reliable solar cell manufacturing, the processes from wafering to cell manufacturing need to be investigated as regards their overlapping influence on the strength of silicon wafers and solar cells.

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