Characterization of damage and mechanical strength of wafers and cells during the cell manufacturing process

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ABSTRACT

Minimizing the breakage rate of silicon wafers and cells during production has been one of the key issues for reliable and productive solar cell manufacturing. However, the root causes of damage or breakage, as well as the mechanical characteristics of manufacturing processes, are not completely understood. In the study described in this paper the change in mechanical strength and the damaging of wafers and cells was analyzed in an industrial cell manufacturing line in order to detect critical process steps and handling operations in certain processes such as etching, diffusion, screen printing and firing. An analysis and discussion of damage sources is presented which offers more insight than the conventional study of breakage rate that is mostly performed by cell manufacturers. In a systematic experimental study, 19 different locations in the production line were investigated. The mechanical strength of 800 wafers or cells at different points in the cell line was subsequently determined using the four-line bending test and the statistical parameters for the Weibull distribution. It was discovered that dramatic changes in strength occur at different process steps because of the change in defect structure; there were also found to be several positions at which no further damage was detected. This method of investigation can therefore be used as a fingerprint of a cell line in respect of yield and breakage rates. Individual processes can be identified that indicate high damage potential, although the actual breakage could occur in a subsequent process step.

Introduction

Crystalline solar cell technology still dominates the PV market [1,2]. The production of silicon solar cells, however, needs to be improved with regard to the cost of their manufacture. On the one hand, a higher use of automation and higher throughput for faster processes can decrease these costs. On the other hand, the thickness of wafers has been reduced to 180µm or 160µm in the last few years because the material is still a dominant cost factor [3]; moreover, new cell concepts demand even thinner wafers to achieve high cell efficiencies [3]. As a result of the use of advanced automation with higher throughputs and lower wafer thicknesses, the wafers are subjected to higher static or dynamic loads, and thus they are more susceptible to damage or fracture.

As reported in the literature, investigations regarding the influence of cell processing steps have mostly focused on the damage-etching and texturing steps at the beginning of the cell manufacturing process [4–10]. Evidently, the damage from the wire sawing process is removed by etching, and the strength of the wafers consequently strongly increases, depending on the chosen texturing process or etch depth. Other researchers have investigated in more detail the metallization process at the end of the cell manufacturing procedure [11,12]. While texturization and metallization are very important process steps, other process or handling steps are largely neglected. There seem to exist only a few documented analyses (for example Chen et al. [13] and Micciche et al. 14]) which deal with a sequence of process steps and their influence on the damage and strength of wafers. More recently, there have been detailed investigations regarding damage to wafers caused by handling operations: these investigations show that grippers deform wafers and cause tensile stress fields. Tensile stresses can lead to the failure of a wafer if a critical defect, mainly a critical crack length, in the wafer is put under load [15]. A statistical evaluation of different gripper techniques showed that handling causes damage to wafers, but the level of damage can vary depending on the gripper technology used [16]. Furthermore, it was found that impact loading on the wafer edges can be harmless if the combination of wafer thickness and impact load is below a critical value [17]. In summary, detailed information is available about the influence of individual process steps on the mechanical wafer strength or damage, but there is only a limited understanding so far regarding the influence of the handling steps. Thus, it is difficult to predict wafer damage and strength during the entire cell manufacturing process, and analyses of the complete process line are necessary.

> "A crucial consideration for breakage is not only the damage but also the critical load."

The root causes of the damage or breakage of wafers, however, during cell manufacturing are not completely understood, especially in the handling steps. It is important to note that in brittle materials, such as silicon wafers, a crucial consideration for breakage is not only the damage (cracks, notches, etc.) but also the critical load. Damage and breakage can therefore occur at different stages in cell manufacture. Furthermore, it is insufficient to analyze just the breakage rate. A quantitative and systematic method is required for measuring the intensity of damage and for detecting critical steps in a process line. In combination with ordinary or random root causes, such a quantitative method would provide information about systematic influences on wafer strength as a part

Material	multicrystalline
Dimension	156mm × 156mm (±0.5mm)
Thickness	200µm (±20µm)

Table 1. General properties of extracted wafer samples.

of the statistical process control (SPC) along the cell manufacturing line.

This paper presents an analysis of wafer strength at each position in a cell production line. A variable fracture strength can be related to specific process steps or the handling operation. On the basis of these results, any damage to wafers in previous process steps can be observed and correlated to the observed breakage rate.

Sample extraction

Wafers and solar cells were taken out of the Hanwha Q CELLS' cell manufacturing line at 19 different positions. Each wafer and cell was then analyzed regarding their breakage behaviour to correlate the mechanical properties of the wafers with the actual process step.

The substrates were taken out of one production slot; their specific properties are summarized in Table 1. The chosen cell production line was fully automated for a classic Al-BSF cell process cycle, consisting of the main process steps shown in Fig. 1.

Between the process machine steps the wafer substrates were handled by belt magazines and slot carriers using soft handling and robots. No touching and handling of the substrate by operators occurred anywhere along the entire manufacturing line. The material was extracted by hand before and after every process machine, starting with as-cut wafers in the standard original polystyrene transport box. During and after the extraction no wafer was broken until the four-point bending test was performed. The extracted material was stored carefully in separate boxes on which the transport and sawing direction was marked for the mechanical analysis.

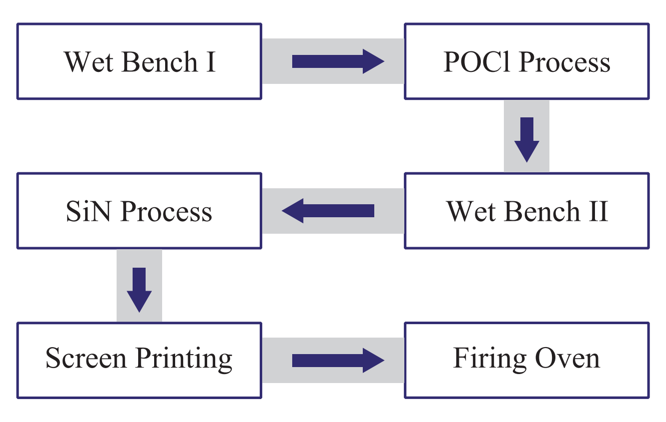


Figure 1. Typical process steps in an actual manufacturing line.

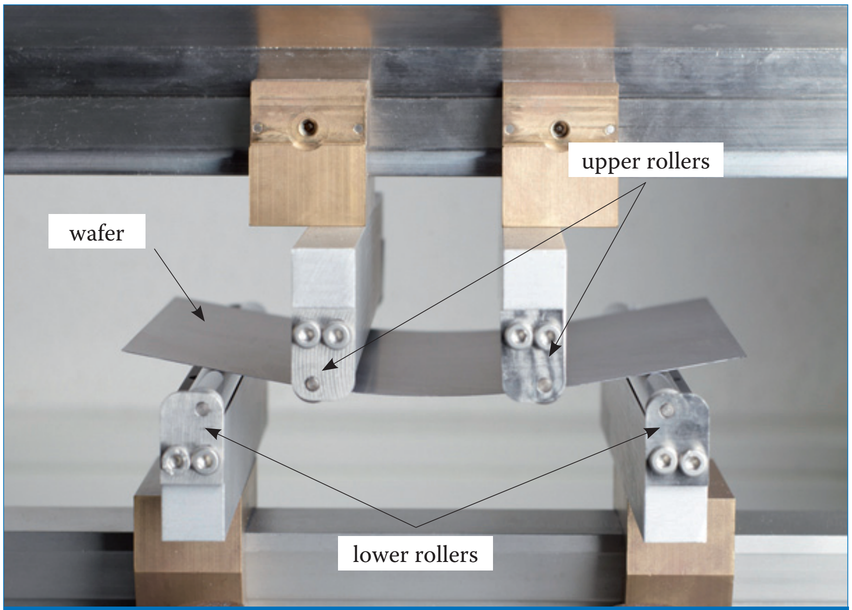


Figure 2. The four-point bending test principle for silicon wafers and cells.

Damage analysis

In order to investigate the damage of the wafers after the handling and process steps, non-destructive or destructive methods can be applied. The resolution of micro-crack detection systems, however, is too low to identify relevant critical cracks (which are in the micrometre range), and a manual analysis by optical and infrared microscopy can be very time consuming. The damage was therefore measured indirectly by wafer strength [6,18,19]; these methods are similar to standard methods for other materials (see, for example, the DIN Standard [20]). Since the strength of a brittle material is defined by the largest defect in the stress field of the loaded wafer/cell, the changes in defect type and size can be determined by measuring the material strength. A statistical approach is therefore used, namely the Weibull distribution [21], which indirectly represents the defect distribution and requires no detailed information about the defect type. Statistical parameters can then be compared for different process steps, and the significance of changes can be analyzed. To ensure reliable results, it is necessary to evaluate 30 to 50 wafers/cells for each position in the process line.

The wafer strength was measured using a four-line bending test, which is more commonly known as the 'four-point bending test' [20]. The set-up is shown in Fig. 2: a parallel set of loading and support rollers bend the wafer uniaxially until the wafer breaks. The fracture force and fracture deflection are derived from the force-deflection charts resulting from the experiments. The set-up geometry consisted of a load span of l = 110mm between the lower rollers and b = 55mm between the upper rollers; the rollers had a diameter of 10mm and were covered by a polymer tape to reduce contact pressure. In this investigation the wafers were placed on the experimental set-up with the sawing direction parallel to the rollers for wafers at process positions P1 to P7 (see Fig. 5). For wafers at positions P8 onwards, a reliable detection of the sawing direction was not possible. The wafer direction can therefore vary within a single batch. After screen printing, the busbars were aligned in parallel to the rollers. The sunny side of the wafers and cells was placed in the constant tensile stress field within the inner rollers for the four-point bending test. A strength reference was determined by testing two batches of untreated wafers, in both parallel and perpendicular orientations with the sawing direction. The reference represents the mechanical preconditions of the wafers at the beginning of the manufacturing process.

The four-point bending tests were performed on a ZWICK 1445 universal testing machine. The force was measured by a 500N load cell, and the deflection was measured by the position of the machine truss. The mean thickness of every wafer was measured by the weight in order to take into account thickness variations within the batch. The fracture stress was determined by the finite-element (FE) method based on parametric 3D shell models, which considers large deflections of the wafers and contact behaviour between the rollers and the wafer (see Fig. 3(c)). For solar cells with metallization, extended layer shell models were used to calculate a fracture stress of silicon, as described in Kaule et al. [22]; the mean thickness and the resulting fracture force and deflection from the experiment were used as input data for the FE models. The fracture stress was defined as the maximum first-principal stress in the silicon wafer.

The Weibull distribution [21] was used for a statistical evaluation of the fracture stresses of every batch. This distribution function is based on weakest-link theory and is commonly used for brittle materials such as silicon: the two function parameters are the characteristic fracture stress σ_θ, at which 62.3% of all samples fail, and the Weibull modulus m, which represents the scattering. The Weibull parameters, estimated by the maximum-likelihood estimation, as well as the confidence bounds, were determined in accordance with the ASTM standard [23].

Experimental results

The results of the strength and damage analyses are given in the following sections, beginning with a presentation of the experimental data, followed by the statistical parameters. The fracture stresses of every wafer were calculated by considering the thickness and fracture deflection using the FE model. Interestingly, while performing the experiments there was no breakage of wafers or cells due to process or handling steps. Thus, it is important that the invisible damage caused in the manufacturing process is analyzed by strength tests.

> “It is important that the invisible damage caused in the manufacturing process is analyzed by strength tests.”

The force-deflection curves were first compared with those derived from the FE model (Fig. 3(a) and (b)). The slopes of the curves represent the stiffness of the wafers; the thickness of the wafer and its variation dominate the variation in stiffness, i.e. the variation in slope. There were only small deviations in mean thickness, which can be seen by the small scattering of the slopes within the batch (Fig. 3(a)). In Fig. 3(b) a comparison of an experimental and simulated data curve is shown: the two data sets are in close agreement, so it can be assumed that the experimental procedure of the four-point bending test was performed correctly and that the model sufficiently represents the mechanical behaviour and the fracture stress. On the basis of these data, the

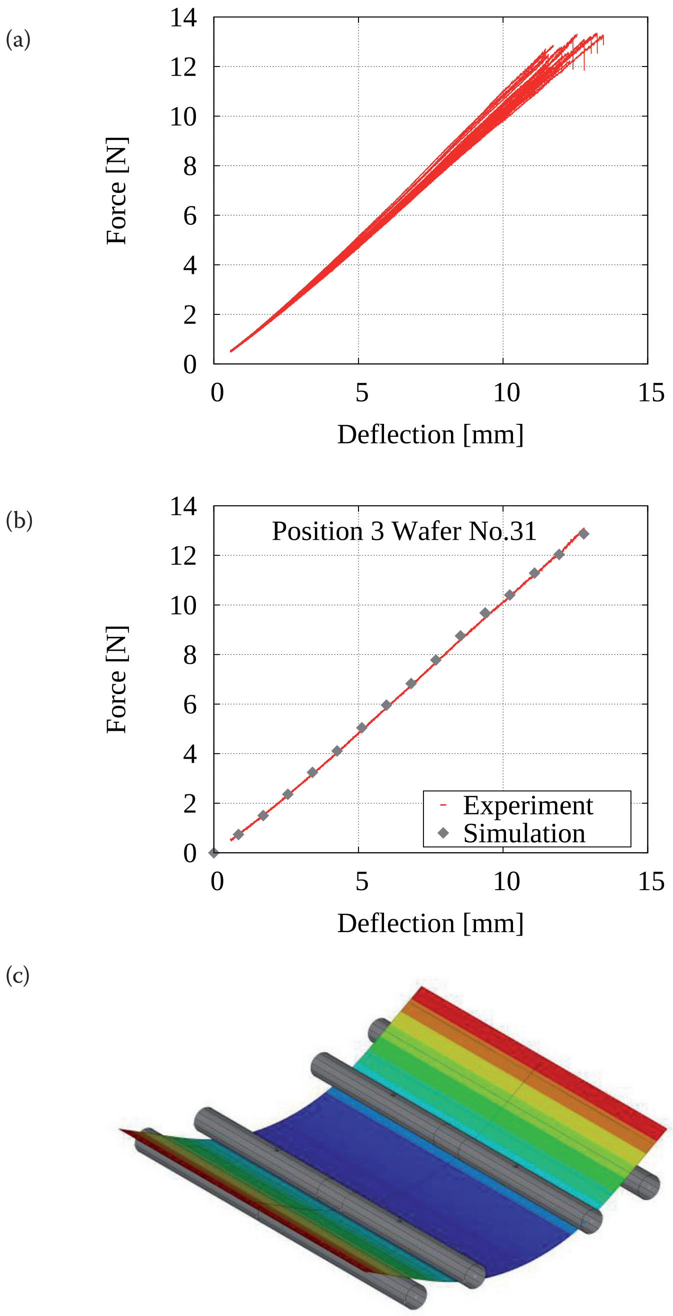


Figure 3. Force-deflection curves from the four-point bending test, and the FE model image: (a) mechanical behaviour of wafers taken from manufacturing position P3; (b) comparison of experimental and simulated data points (wafer no. 31 at P3); (c) calculated deflection of the silicon wafer subjected to four-point bending.

fracture stresses were calculated using the FE model (Fig. 3(c)).

Fig. 4 shows example strength distributions and Weibull plots for the reference batches, i.e. the initial mechanical strength of the wafers used. The distribution of the detected fracture stresses at the beginning (Fig. 4(a) and (b)) and at each extraction position is adequately represented by a Weibull distribution (Fig. 4(c)). Thus, in the following, only the characteristic fracture stress (σ_θ) and the Weibull modulus (m) are used to characterize the mechanical properties of each wafer batch (see Table 2). For the reference batch P1, no significant difference between the characteristic fracture stresses regarding the loading direction could be observed. When the wafers were loaded in parallel and perpendicularly to their sawing direction, 63.2% of the tested wafers failed at tensile stresses of 144.2MPa and 146.2MPa, respectively. In contrast, the Weibull modulus is significantly different. The scattering of fracture stresses depends on the wafer orientation during the four-point bending test. In this case the scattering was higher for wafers that were tested perpendicularly to their sawing direction. Thus, the confidence bound ranges of the characteristic strength and the Weibull modulus must be considered if a comparison is made with data from a subsequent production process.

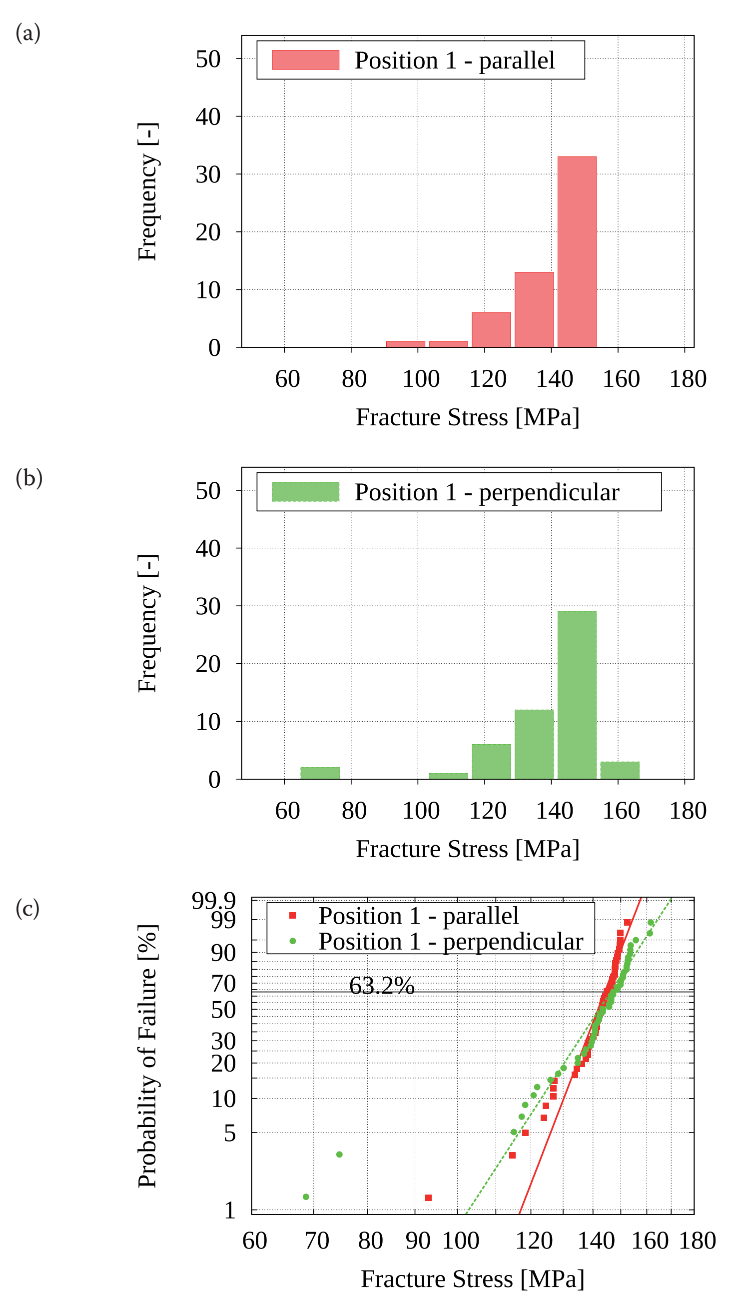


Figure 4. Distribution of fracture stresses of untreated reference wafers: (a) histogram of fracture stresses (parallel to sawing direction); (b) histogram of fracture stresses (perpendicular to sawing direction); (c) Weibull diagram of reference wafers parallel and perpendicular to the sawing direction.

The characteristic fracture stresses and Weibull moduli are summarized in Table 2 for all wafer and cell extraction positions. The strength behaviour for some batches of wafers and cells exhibits significant differences between the characteristic fracture stresses and the Weibull moduli. The significance is rated by the confidence bounds, which may overlap (no significant difference in strength and damage) or may not overlap (significant difference in strength and damage).

A visualization of the characteristic fracture stresses and Weibull moduli vs. the extraction positions in the process line is presented in Fig. 5; the first two bars of P1 and their confidence bounds represent the reference values. It can be clearly seen that there is an initial increase to 199MPa in the characteristic fracture stress after the first etching process, while the Weibull modulus remains within the range of the confidence bounds of the reference parallel and perpendicular batches. The Weibull modulus depends on the loading direction, which cannot be assured for all tested wafers and cells. Thus, similar scattering of the fracture stresses for subsequent process steps can be expected to lie within the range of the reference batches for a Weibull modulus m between 13 and 22. Differences in the Weibull modulus were, however, observed and interpreted between individual extraction positions.

The next stage of increase in fracture stress σ_θ was observed after the diffusion process (batch P7): the characteristic fracture stress rises up to 208MPa. The final increase in σ_θ was determined after a handling operation (batch P14), with the characteristic fracture stress reaching its maximum of about 218MPa after deploying the silicon nitride mounting device. Almost at the end of the manufacturing line, after firing the cell contacts, a decrease of σ_θ to 198MPa was measured. In summary, four processes were detected that showed a significant change in the characteristic fracture stress, but overall the strength of a wafer was increased by about 34% during the process line until the wafer became a complete solar cell.

Extraction position	σ_θ [MPa]	m [-]
P1[1]	144.2 (142.6…145.8)	22.1 (18.0…25.8)
P1[2]	146.2 (143.5…149.0)	13.1 (10.7…15.3)
P2	142.4 (139.9…145.0)	18.5 (13.9…22.5)
P3	198.8 (194.8…202.8)	16.4 (12.4…20.0)
P4	194.0 (190.9…197.2)	21.0 (15.7…25.6)
P5	204.2 (200.1…208.4)	16.7 (12.5…20.3)
P6	193.6 (187.9…199.5)	11.9 (8.8…14.7)
P7	207.6 (202.5…212.9)	13.5 (10.1…16.5)
P8	214.1 (210.9…217.4)	22.1 (16.6…26.9)
P9	206.9 (201.6…212.5)	12.9 (9.7…15.7)
P10	208.2 (205.8…210.6)	29.4 (22.0…35.8)
P11	206.1 (200.7…211.7)	12.6 (9.4…15.3)
P12	196.7 (189.3…204.4)	8.8 (6.6…10.7)
P13	205.0 (199.3…210.9)	11.9 (8.9…14.5)
P14	218.0 (213.5…222.7)	15.9 (11.9…19.4)
P15	218.8 (214.6…223.1)	17.2 (12.9…21.0)
P16	212.9 (207.1…218.9)	12.1 (9.1…14.8)
P17	212.4 (208.2…216.8)	16.7 (12.5…20.3)
P18	197.5 (192.1…203.2)	12.2 (9.1…15.0)
P19	193.9 (190.1…197.7)	17.3 (13.0…21.1)

[1] rollers parallel to saw marks
[2] rollers perpendicular to saw marks

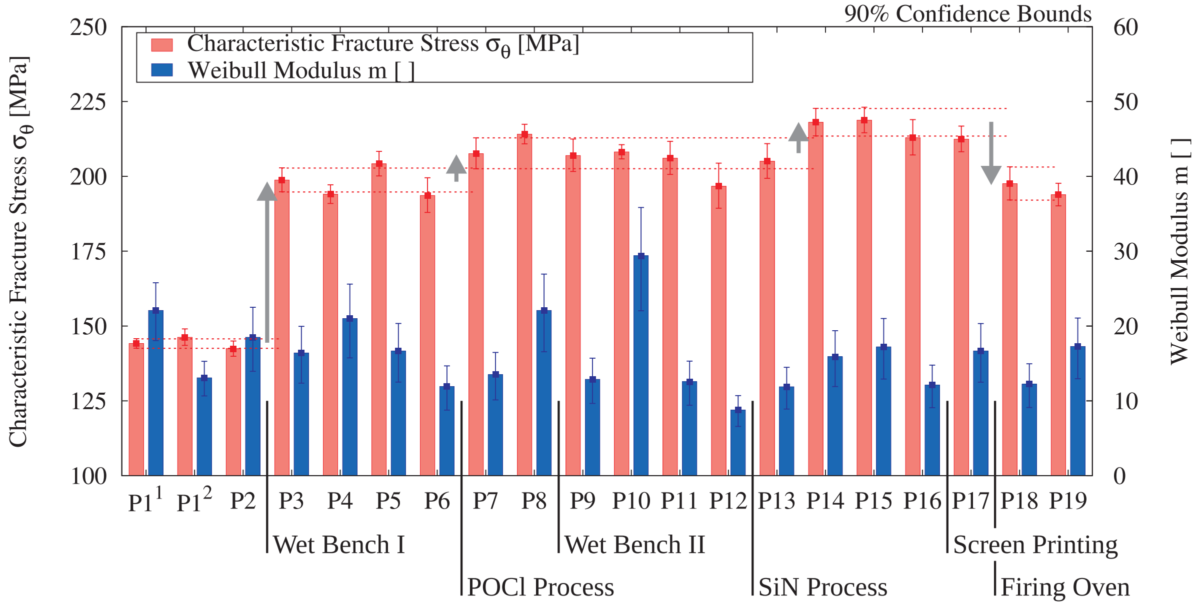
Table 2. Characteristic fracture stresses, Weibull moduli and 90% confidence bounds (in parentheses) of wafer batches at every extraction position (P1 = reference batch).

"Overall the strength of a wafer was increased by about 34% during the process line."

Strengthening and damaging of wafers

The results demonstrated that the strengthening and damaging of silicon wafers due to the manufacturing process can be measured by a statistical characterization of wafer strength. The estimated statistical parameters showed significant differences, and clear trends were visible in the experimental data. Various observations will now be discussed in detail.

The possibility of damaging a wafer exists at many positions in the manufacturing line, as highlighted by Fig. 5: for instance, the characteristic fracture stress increases and decreases between positions P3 and P9 as a result of two etching processes and one diffusion process. Although it was not possible to detect significant differences between manufacturing positions, a trend could be seen. The variation in the Weibull modulus during the manufacturing process confirmed this effect, because a change in this value correlates to a change in the defect distribution. In particular, the Weibull modulus tends to decrease from extraction positions P4 to P6. This means that



[1] rollers parallel to saw marks
[2] rollers perpendicular to saw marks

Figure 5. Distribution of characteristic fracture stresses (σ_θ) and Weibull moduli (m) at all cell line extraction positions.

an effect is present that changes the fracture stress distribution without a significant shift in the characteristic fracture stress. It is important to note that after the strengthening by POCl diffusion (P7 onwards), the fracture stresses remained nearly constant until P13. A significant departure from the confidence bounds of the Weibull modulus was observed between extraction positions P9 and P10, which is a handling step only. As a result of handling, the defect structure may change, causing a higher scattering of the fracture stress by having no effect on the characteristic fracture stress.

The observed wafer strengthening trend between extraction positions P12 and P14 featured a rising characteristic fracture stress and an increasing Weibull modulus; the deposition of SiN, as well as several handling steps, takes place at these positions. As the Weibull modulus increases, the scattering of the fracture stress of strength wafers decreases because of a narrower defect distribution. The rising characteristic fracture stress, however, is more difficult to explain. This effect represents a strengthening of the wafers due to handling only in these process steps. Currently, there are two hypotheses. First, the SiN process is assumed to strengthen the wafers similarly to the POCl process, but random damage situations during processing and handling in the line caused different defect distributions for the extracted batches P12–P14. Therefore, wafers from P14 might show less of this random damage than those from P12 and P13, which would result in higher fracture stress values. Second, similar strengthening effects due to handling have been seen before [16]. Handling operations could therefore affect the strength of wafers in a positive way. However, the reasons are assumed to be the intrinsic material effects in silicon as a result of cycling [16]; these effects are not yet fully understood and further research is necessary.

In summary, the highest strengthening of the wafers was observed after the first etching and texturing process. This effect is well known and can be correlated with a change in the surface damage intensity of the wafers. Damage such as small cracks caused by wire sawing vanish, and the tips of larger cracks become blunted [6,7,10]. The POCl diffusion process also changes the surface properties. High-temperature processes and the presence of oxygen strengthen the silicon by the formation of a silicon oxide layer in the crack, thus closing it [24,25]. In this case an increase in the characteristic fracture stress is much smaller than if cracks are removed, as in the etching process.

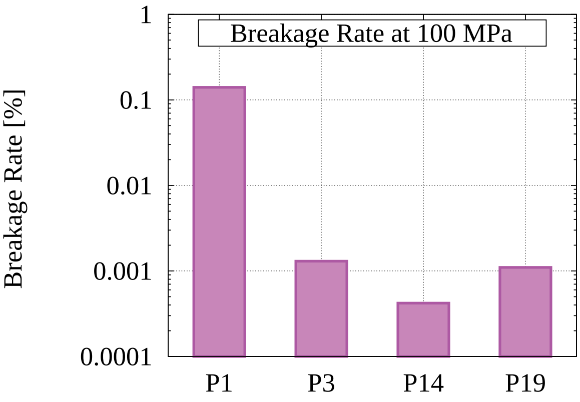


Figure 6. Predicted breakage rate of wafers extracted at different stages of the manufacturing process, for a chosen load of 100MPa (prediction based on determined statistical strength parameters).

The final strengthening effect takes place at position P14, after a handling operation. In the previous section different hypotheses were mentioned regarding this effect, which requires further analysis. The final process step is firing of the contacts, from P17 to P18. A high-temperature process causes internal mechanical stresses in the material because of a thermal expansion mismatch between the silicon and the contacts on the front and back sides. This causes a bowing of the solar cell [11,26], and the residual stresses can reduce the strength of the cell. The residual stress fields due to bowing are tensile stresses on the sunny side of the solar cell. Since this side was tested in the experiments, the drop in fracture stresses most likely results from these residual tensile stresses, which lower the load capability and the strength. Further damage in the firing process step, however, may also contribute to the lower strength of solar cells. Nevertheless, the solar cell in this inspected cell line increases in strength by 34% compared with a virgin as-cut silicon wafer. Although all of the strengthening and damaging effects could similarly be found in other cell lines, these results represent the strength fingerprint of the cell manufacturing line.

Breakage rate estimation

A breakage rate can be estimated on the basis of the fracture stresses of all the wafers and cells used in this investigation. In practice, only the weakest wafers are of interest because they fail first. Thus, for the estimation the focus will be on only the lower end of the fracture stresses of each strength distribution. Fig. 6 shows the probability of failure or estimated breakage rate for an assumed load of 100MPa (neglecting the strength size effect): such a load could be caused by a handling or process step during the manufacturing process. It can be seen that the untreated wafers at the beginning of the production line have the highest probability of failure (0.1%). After the etching step, the breakage rate decreases to approximately 0.0013%, reaching a minimum of less than 0.00042% after the unloading of the SiN mounting device, at position P14. Compared with an untreated as-cut wafer, the breakage rate of a finished solar cell is very low: for a load of 100MPa, the probability of failure decreases during manufacturing to 0.0011% (a factor of 25). Solar cells are therefore mechanically more reliable than as-cut wafers.

It should be borne in mind that the damage potential determined by a breakage rate estimation represents the systematic influence of the manufacturing line on strength and breakage. It can thus be interpreted as a fingerprint of the cell line.

The estimated breakage rate does not represent the total wafer breakage in the line. The real breakage rate is always the sum of the systematic and random damage which causes breakage. If the number of systematic causes (from the Weibull analysis in this paper) is known, as well as the total amount of wafer breakage (resulting from the statistical process control), the contributions of systematic and random damage sources can be determined in order to optimize individual process or handling steps or to benchmark technical improvements in a production process.

Conclusion

A crucial task in solar cell manufacturing is the reduction of the breakage rate in order to achieve a reliable and efficient production process. This paper has presented a way to analyze the damage potential of individual procedures as well as entire manufacturing process lines. With the help of focused systematic mechanical testing and a statistical analysis of wafer strength, a critical process step can be detected and the breakage rate can be estimated. There are three significant strengthening or damaging steps in a solar cell manufacturing line:

1. The first and major process step is the etching and texturing process, which increases the characteristic fracture stress by 40%.

2. Subsequent process steps, such as POCl diffusion, cause a small strengthening increase of 4%.

3. After the cell contacts are fired, the strength decreases by 9%; the final strength of a solar cell, however, is increased by about 34% in comparison to that of the as-cut wafer at the beginning.

> “The variation in the Weibull parameters is important for identifying a change in damage distribution of the wafers during the manufacturing process.”

The variation in the Weibull parameters is important for identifying a change in damage distribution of the wafers during the manufacturing process: different trends were observed, which need to be analyzed in more detail to gain a more comprehensive understanding of the impact on defects and the strength associated with individual process steps. Moreover, the statistical Weibull analysis has to be compared with data from the statistical process control in order to enlarge the database and to identify the critical steps in a manufacturing process.

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Frank Wegert received his Diploma degree in mechanical engineering from Rostock University in 1990. He works for several international companies as an expert in machine design and process engineering. He joined Hanwha Q Cells in 2006 and is currently a senior staff expert, responsible for technical key projects in the development and optimization of machines in cell and module production as well as handling technologies.

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