TOWARDS THE CORRELATION OF MECHANICAL PROPERTIES AND SAWING PARAMETERS OF SILICON WAFERS

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ABSTRACT: The price for silicon used in the photovoltaic industry has increased dramatically over the last few years, due primarily to its high purity requirement and limited supply. Thus, for reducing the production costs, it is important to minimise the thickness and the breakage rate of the silicon substrates ("wafers") through the entire manufacturing chain of solar cells. Today, silicon wafers are obtained from cast mono- or multi-crystalline silicon ingots using the multi-wire slurry saw (MWSS) technology. This machining process introduces defects, which are responsible, among other factors, for subsequent wafer breakage. It is therefore important to understand the relationship between the sawing parameters, the resulting (sub-) surface defects and the wafer breakage yield. In this study, the fracture strength, the crack depth distribution and the surface roughness of wafers are investigated with respect to several sawing parameters, as the abrasive grain size, its concentration in the slurry, the table speed and the wire tension. A polishing technique has been used to reveal the cracks depth, from which was measured its distribution. Furthermore, non-destructive roughness measurements have been carried out and yield strength of the wafers has been measured. Preliminary results indicate the predominant role of the abrasive grain size in the sawing quality, as well as the variation of its quality along the wire direction.

Keywords: Defects, Silicon, Substrates

1 INTRODUCTION

To produce Si solar cells, high quality wafer must be used. Starting from monocrystalline or multicrystalline ingots the first step consists in cutting Si into blocks of the right dimension, with band or wire saws. The next step is multi-wire slurry sawing (MWSS), during which the wafers are cut to their nominal thickness. These steps are crucial, as they will, in large part, define the strength of the wafers to mechanical solicitation during the various cell processing steps, but also up to the module level [1]. Although sawing wafers down to 100 µm thickness has been shown to be achievable [2], thin wafers tend to break too easily during post-cutting handling and subsequent processing [3] and indeed the minimum thickness of the wafer is hardly below 200 µm in production. Thus, a large amount of silicon is only present for mechanical stability, which in turn increases the total cost of the cells. Two possibilities exist to make thinner wafers. First, the wafers can be mechanically or chemically thinned after being cut. This solution will produce mechanically strong wafers, but the silicon removed during this process is lost and this extra step is expensive, which does not diminish the price of the cells. The other solution is to directly cut thinner wafers with enhanced mechanical strength, but this requires a better knowledge of the sawing process.

In the multi-wire slurry saw (MWSS) technology [4], a thin steel wire is running across the ingot, transporting a mix of lubricant and abrasive. This abrasive, usually SiC, will cut the silicon, but it will at the same time create surface defects. These defects, mainly cracks, can penetrate into the wafers, up to 10 – 20 µm. After the cut, the wafers are washed and etched, in order to have a proper surface for processing the wafers into solar cells. This etching will remove the less deep cracks, but the deepest cracks will stay, thus depreciating the fracture strength and reducing, hence, the production yield.

The mechanical strength of a wafer depends mainly on the size of its surface cracks. Silicon being a brittle material, the cracks induces discontinuities in the stress field when the wafers are mechanically solicited. These discontinuities are such that the stress intensity at the crack tip will increase greatly [5, 6]. Fracture mechanics provides a useful tool to determine whether a crack stays immobile or propagates, the latter causing the wafer breakage. In the simplest cases, analytical methods can be used to make such calculations, but usually, the help of finite elements methods is required [7]. Basic elements of fracture mechanics of Si wafers and strength determination are given in the paper of Wasmer et al, [5].

Apart from cracks, the surface roughness can produce similar effects, the valleys acting as stress concentration sites. The combination of these two effects will determine the final fracture strength. For a given crack shape, the deeper it is, the lower the fracture strength will be. Shape, position and loading mode will also affect the fracture strength. Furthermore, the thickness of the wafer plays an important role, as for a given bending deformation the stress at the surface of a wafer is less important for a thin wafer than for a thicker wafer. Thus, cutting thinner wafers provides another advantage, apart from economical considerations: they resist better to an imposed bending deformation.

Some groups have been studying the dynamical behavior of the wire with the help of hydrodynamical simulations [8-10], its vibrations and their implications on the different cutting regimes, depending on the distance between the wire and the silicon ingot. Others have been developing a model to qualitatively predict sawing quality, based on a "rolling – indenting" model

[1, 2, 7, 11, 12].

This work attempts to shed some light on the influence of the sawing parameters on the sawing quality. Surface analysis tools are used, like SEM, profilometry, surface polishing experiments, and mechanical testing. As each of these tools has advantages and drawbacks, only a combination of them can give a precise understanding of the surface and sub-surface defects of sawn wafers.

SEM observations, having a high resolution, give poor indication on the depth of the features observed and no information on the sub-surface defects. Furthermore, such observations are time consuming and as the analyzed area are very small (1 mm^2 at most), the question of the representativity of such measurement is always present.. On contrary, visible light profilometry is much faster, non destructive and more representative, as the analyzed surface can be much bigger. The polishing method, despite requiring a long sample preparation, is able to give information on cracks depth and quantity, which are most useful to understand the relation between crack depth and fracture strength. Finally, the bending test provides the prime tool to measure the fracture strength. But as Si is a brittle material, the fracture strength is given by a probability distribution, which implies that many wafers need to be tested to provide relevant results.

The sawing parameters investigated include the abrasive size and concentration, the wire tension and the ingot feeding speed. These parameters have complex influences, in addition to influencing the sawing quality, as the feeding speed will also play a role in the productivity of the process, and the abrasive size will have an influence on the kerf loss. Finally, a correlation between the different measurements is made.

2 EXPERIMENTAL METHOD

2.1 Sawing parameters

The 250 µm thick wafers are sawn by an HCT using monocrystalline, pseudo-squared 125x125 mm^2 ingots, into 250 µm thick wafers. The investigated sawing parameters are the wire tension, the ingot table speed, the abrasive size distribution and the abrasive concentration in the slurry. The lubricant used is a polyethylene glycol (PEG) and the abrasive is standard grit distribution SiC. The parameters are varied across the widest range possible, dictated by technical considerations. The range of the parameters used is given in Table I. The given grit size is the median size of the abrasive. The standard sizes used correspond to F1200 (finest abrasive, median size 3µm), F800, F500 (middle abrasive, median size 12.8 µm), F400 and F360 (coarsest abrasive, median size 22.8 µm). The slurry flow rate is set at 50 kg/min and the wire speed at 11.5 m/s.

Table I: variation of the sawing parameters

Parameter	Min	Middle	Max
Wire tension [N]	21.8	30	38.2
Table speed [µm/min]	173	450	727
SiC/HS20 [kg/l]	0.57	1	1.43
Grit Size [µm]	3	12.8	22.8

2.2 Crack depth distribution measurement

The goal is to quantify the cracks depth distribution inside the wafers. To do that, a sawn wafer is cleaved in smaller samples, which are then glued together and embedded in resin at a small angle (around 5 °) with respect to its surface. Then, a mechanical polishing is performed until the whole section of the wafers is visible. Finally, gentler polishing is applied to obtain a mirror-like surface, with cracks clearly revealed. The sample is then observed with an optical microscope to measure the number and depth of cracks present. For each sawing condition, only one sample is made, after the reproducibility of such a measurement is confirmed by preparing several samples out of the same sawing conditions. The measurements are carried out on a length of 3.5 mm in order to have a representative distribution of the crack depth.

This preparation is done so that cracks parallel to the wire direction are observed, and, in order to see whether the cracks are preferentially oriented or not, the same preparation is done, but in a direction perpendicular to the wire for a few set of samples.

Furthermore, the influence of position on the wafer is analyzed. Samples are made near the entrance, the middle and the exit of the wire to see if the crack distribution is changing. The position of the different measurements is presented on the sketch on Figure 1.

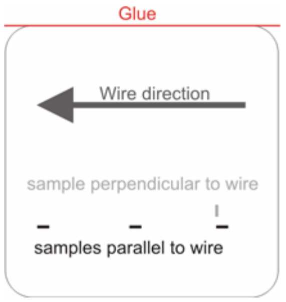

Figure 1: Sketch of a wafer with the different positions of crack depth measurement samples.

2.3 Roughness measurements

The roughness is measured with a contact-less visible light profilometer from AltiSurf. The measurement length is, according to the norm ISO 4287, 5.6 mm. For each sawing parameter, three wafers are measured. On each wafer, roughness was measured on 18 points, 9 on each side of the wafer. For each point, 3 measurements parallel to the wire direction and 3 measurements perpendicular to it were made. These measurements were made to see the evolution of surface morphology during the cut and whether the roughness had a preferential orientation or not. From these data, the average roughness parameter Ra was calculated. The mean result over the three equivalent measurements was finally calculated for each location.

2.4 SEM observation

SEM samples were cleaved from wafers and glued with conductive glue on a sample holder. The images were taken with a Hitachi S4800 FEG SEM at 1kV.

2.5 Wafer strength tests

The wafers were tested as described in the article by Wasmer *et al* [5] with the equi-biaxial, “ring-on-ring” test. In order to obtain meaningful statistical values, a number of 30 wafers were tested for each sawing parameter. The wafers which breaks outside the inner ring are excluded form the statistics; hence, the fracture strength of about 25 samples was recorded for each sawing parameter tested. These tests were conducted for four sawing parameters, representing the most different ones, in order to validate the other analysis methods.

3 RESULTS

3.1 Crack depth distribution

The sawing quality has to be defined with respect to the type of measurement done. As only a small area of the wafer was analyzed, it is obvious that the probability to observe the deepest crack in the whole wafer is small. Due to the large number of cracks observed, it is possible to fit an exponential curve to the distribution measured in the form $f(d) = Ae^{-Bd}$, d, A and B representing, respectively, the depth of the crack, a fitting parameter and the rate parameter of the distribution. The crack depth distribution and the corresponding fit for a cut are shown on Figure 2. In order to find a comparison between the different cuts, a crack depth characteristic length, given by *1/B* from the formula above, is used. This characteristic length varies between 1 and 10 µm. The main parameter influencing this difference is the abrasive grain size, as shown in Fig. 3. For coarse abrasives, the influence of the other parameters is more important than for finer abrasives, so that it is possible to have a better cut with the right set of parameters and coarser abrasive that with wrong sawing parameters and finer abrasive. But the difference in crack depth between abrasive F500 and F800 is more important and all cuts made with F800 are better (smaller 1/B value) than the cuts made with F500.

The only set of wafers cut with the finest abrasive, namely F1200, has not the shallowest crack depth distribution, but comes on the fourth place in an ascending order. However, it has the lowest cracks density of all the wafers measured.

3.2 Roughness

It has been observed that the direction of roughness measurement has a negligeable influence on the results. Thus the analyzed measurements were taken perpendicular to the wire direction, as for the crack depth distribution measurement.

As for the cracks depth, the influence of sawing conditions can clearly be seen on Figure 4, with the same tendencies than for the crack depth distribution. The average roughness parameter *Ra* is ranging from 0.3 to 1.7 µm, which means that for the worst cut, the roughness represents more than 1 % of the total thickness of the wafer.

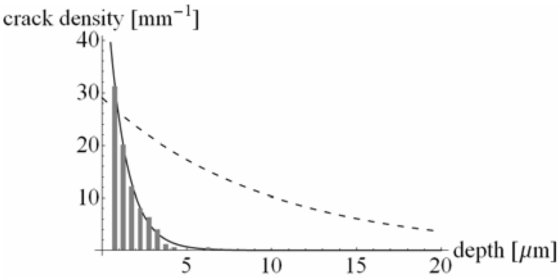

Figure 2: Crack depth distribution for the wafers cut with the smallest abrasive. The plain exponential curve is fitting the measured distribution quite well. As a comparison the dashed curve represents the fitted distribution of the wafers cut with the coarsest abrasive

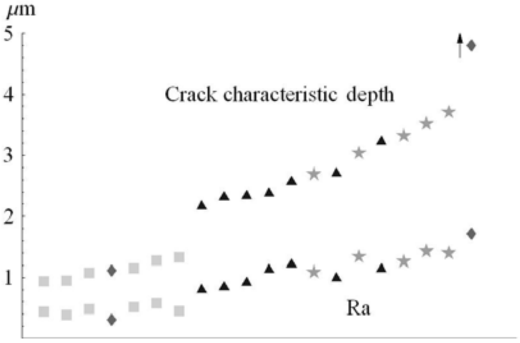

Figure 3: Crack depth characteristic length (l/B) (top) and average roughness (bottom), sorted in crack depth ascending order. The diamonds on the left represent the sample cut with the finest abrasive, the ones on the right represent the cut with the coarsest abrasive. Squares are cut with small, triangles with standard and stars with coarse abrasive.

3.3 Wafer strength tests

Results from bending tests are presented in Figure 5. The yield stress distribution has been fitted with a Weibull distribution ($P(\sigma) = \exp\left[-(\sigma/\sigma_0)^m\right]$where m is the Weibull modulus and σ_0 is a characteristic strength), whose parameters are given in Table II. It can be seen that the toughest set has a larger standard deviation than the weaker set, but the strongest wafer tested of the strongest set broke at twice the load of the strongest wafer of the weaker set.

Table II: Mean stress, standard deviation (in MPa) and Weibull distribution parameters (σ_0 in MPa)

	Mean	Standard Deviation	Median	σ_0	m
Smallest abrasive	800	230	780	890	3.7
Coarsest abrasive	580	50	580	610	11.5

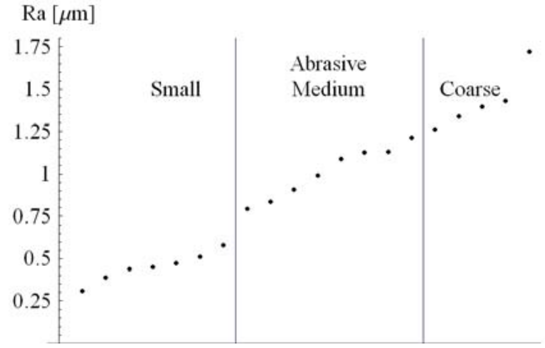

Figure 4: Mean roughness for the different sawing conditions, sorted by increasing Ra, for 20 cuts performed in different conditions. The difference in roughness between the small and medium abrasive is clearly visible.

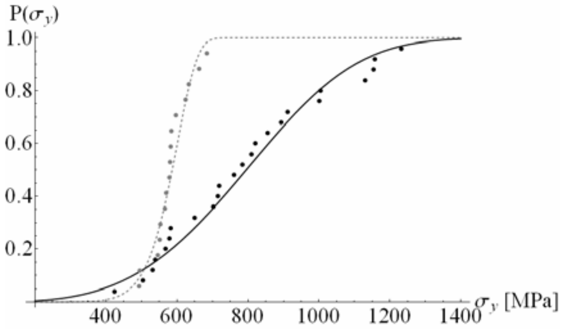

Figure 5: Yield stress distribution for two sets of wafers sawn with different conditions, in gray with the coarsest, in black with the finest abrasive. The other sawing parameters remain the same

4 DISCUSSION

From Fig. 3 the roughness and crack depth measurements give the same tendencies and a correlation between the two measurement methods is found., making roughness measurement a first qualitative tool to estimate sub-surface defects depth. In particular, the stricking features is that the wafers cut with the coarsest abrasive (blue stars on the right) have much deeper cracks and bigger roughness than all other cuts. However, the cut made with the finest abrasive (blue stars on the left), despite having the lowest roughness, does not have the lowest crack depth. In fact, if the sawing parameters are chosen well, crack depth of wafers sawn with coarse abrasive can be lower than wafer sawn with medium abrasive and wrong cutting parameters.

It has to be noted that if the crack depth and roughness are strongly dependent on the abrasive size, the other sawing parameters still have an influence, which is not identical for the two types of measurements.

The fracture strength distribution of two sets of wafers, respectively the ones cut with the coarsest abrasive and the ones cut with the finest abrasive shows that the sawing quality measured by crack depth distribution or roughness is reliable. The two important indications useful from such measurements are the mean and the dispersion. Indeed, as a high mean fracture strength gives tough wafers, but if the dispersion is important, some wafers can still break at a low load. As these breakages are not predictable, they will result in wafer breaking during subsequent production and thus loss of productivity. A set of wafer with a low fracture strength dispersion but lower mean fracture strength will give more predictable wafer breakage. Thus, if all the processes in the production line are designed not to induce too important stress, the breakage rate can be managed to be low. Finally, the wafers sawn with the finest abrasive have a high fracture strength dispersion, which indicates that these parameters are not the best ones possible. It is probable that as the abrasive particle are small, they are not as efficient as the larger abrasive grains and that the cutting speed was too fast, which will cause very important stresses during sawing, producing few but important cracks.

5. CONCLUSION

The present results show that assessing the sawing quality of a wafer can be obtained by several methods. But ultimately, the fracture strength test will determine whether a wafer will break in production or not. As such tests require to break a significant amount of wafers, other methods such as crack depth or roughness measurement can give a first qualitative information on sawing parameters which are likely to be relevant.

Our results show that these sawing parameters have an important impact on the sawing quality, and the most important parameter is found to be the abrasive size. The other parameters investigated, namely the wire tension, the cutting speed and the abrasive concentration in the slurry also affect the quality and the best set of parameters will in turn depend on the abrasive size.

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