INFLUENCE OF ABRASIVE CONCENTRATION ON THE QUALITY OF WIRE-SAWN SILICON WAFERS

A. Bidiville[1], K. Wasmer[2], J. Michler[2], C. Ballif[1], M. Van der Meer[3] and P. M. Nasch[3]

[1] Institute of Microtechnology, University of Neuchâtel, A.-L. Breguet 2, 2000 Neuchâtel, Switzerland
[2] EMPA – Materials Science and Technology, Laboratory of Mechanics of Materials and Nanostructures, Feuerwerkstrasse 39, 3602 Thun, Switzerland.
[3] Applied Materials Switzerland, Precision Wafering Systems, Route de Genève 42, 1033 Cheseaux, Switzerland

ABSTRACT: The sawing parameters have an impact on the depth of the defects in the wafers, and hence on their mechanical strength. However, as sawing is a highly complex system, the wafering industry is still relying on a “trial and error” approach to improve the sawing parameters. In this contribution, the effects of the abrasive concentration are studied with the help of the “rolling-indenting model”, the model most commonly used to describe the sawing process. From roughness and cracks depth measurement correlated with flexure tests, we show that using a lower silicon carbide concentration in the slurry decreases the depth of the defects as well as the roughness and results in a higher breakage strength of the wafers.
Keywords: silicon, sawing, defects

1 INTRODUCTION

The production of crystalline silicon solar cells generally requires the shaping of wafers. These wafers are usually sawn out of an ingot with a multi-wire slurry saw (MWSS). This process step is of prime importance, because it defines the surface quality, but also the wafer strength [1, 2, 3], which plays a major role in the solar cells production yield. Finally, the amount of silicon needed – *i.e.* part of the cost of the cell – is also determined by this sawing step. The optimal wafer should hence be as thin as possible but still have a high resistance to breakage.

The MWSS consists of a steel wire running at high speed on the silicon ingot. Slurry is poured on the wire before it reaches the silicon. This slurry is made of silicon carbide (SiC) particles and a lubricant. The SiC particles are taken up to the cutting zone by the wire and remove silicon by indenting the ingot. At the same time, the table holding the ingot is slowly moved towards the wire, diminishing the distance between the wire and the silicon so that the sawing can keep on. In this system, a lot of parameters may have an impact, starting from the slurry properties (like its rheological behavior, the temperature, the shape of the abrasive, its size distribution or its concentration) to the wire (its tension and speed) or the cutting speed. Furthermore, parameters harder to control might also play a role, for instance the way the wire tension is handled by the saw, the hardness of the silicon ingot or the presence of inclusions.

The prime tool for studying the wafers strength is bending tests. Several studies have already been made to find out which type of tests is best suited in the case of silicon wafers [1, 3, 4, 5], depending on the properties to be studied. Such tests are able to provide the stress distribution at rupture for a set of given wafers, but their major drawback is that they require breaking a large amount of wafers to obtain statistically relevant results. It has been shown that a correlation exists between roughness and crack depth distribution [6], allowing an efficient quality control of sawn wafers in a non-destructive way. But to the authors' knowledge, such a correlation has not been found between roughness and stress-to-rupture yet. An interesting path towards understanding this relationship has been given by comparing wire-saw experiments with lapping [3, 7, 8] and the rolling-indenting model developed by M. Buijs and K. Korpel-van Houten [9, 10]. A result of this model, which describes the lapping process of brittle materials, is that the roughness and the crack depth (as calculated by bending experiments) are correlated. Unfortunately, a direct and simple correlation has been questioned for the case of wire-sawing [11].

In lapping experiments, a sample is pressed against the lapping plate where the slurry is poured. As for wire-sawing, the slurry is made of abrasive particles and a lubricant. Both penetrate within the space between the sample and the lapping plate, where the abrasive particles come into a simultaneous contact with the sample and the lapping plate, thus indenting the sample and causing wear. This interaction between the sample and the particles can be seen exactly like an indentation and so fracture mechanics of indentation should describe the crack propagation into the sample [12, 13]. The relevant parameters for an indentation are the angle of the indenter – which can be related to the lapping particle shape – the maximal indentation force and the indented material properties. Based on lapping experiments, M. Buijs and K. Korpel-van Houten [9, 10] derived an expression for the average peak-to-valley roughness:

$$R_z = \alpha_1 \frac{E_w^{1/2}}{H_w} P_i^{1/2} \quad (1)$$

where P_i is the normal load per load-bearing particle, E_w and H_w are Young's modulus and hardness of the workpiece, respectively, and α_1 is a constant depending on the particle shape. They also determined an expression for the length of the subsurface flaws [9, 10]:

$$c = \alpha_2 \frac{E_w^{1/3}}{K_{Ic,w}^{2/3} H_w^{1/3}} P_i^{2/3} \quad (2)$$

where α_2 is a constant depending on the particle shape and $K_{Ic,w}$ is the fracture toughness of the sample. Finally, the removal rate was found to be given by [9, 10]:

$$Z = \alpha_3 n \frac{P_i^{3/4}}{L_{m,c}} \frac{E_w^{1/3}}{K_{Ic,w} H_w^2} pv \quad (3)$$

where α_3 is a constant depending on the particle shape, n is the number of indenting points on the circumference of the rolling particle, $L_{m,c}$ is the mean size of the load-bearing particles, p is the total pressure and v is the speed of the wire.

From these equations, it can be seen that one of the most important parameters determining the cracks depth (and therefore the wafers strength) is the load per particle. More importantly, this load per particle does not depend on the overall load, but on the abrasive size and on the slurry properties [9]. Indeed, the load per particle is given by [9]:

$$P_i = H_{eff}\left(1-\frac{b}{L_{m,c}}\right)^2 L_{m,c}^2 \qquad (4)$$

where H_{eff} is the effective hardness (depending on the hardness of the sample and of the lapping plate) and b is the distance between the lapping plate (or the wire) and the sample. The ratio $b/L_{m,c}$ depends (among other things) on the lubricating properties of the slurry, *e.g.* its viscosity.

It was already pointed out that the abrasive size has an important impact on the wafers strength [6], but – to the authors' knowledge – no study about the impact of the particles concentration in the slurry on the wafers strength was carried out. In this contribution, sets of wafers were sawn with different abrasive concentrations in order to analyze their impact on wafers properties, such as roughness, crack depth distribution and mechanical strength.

2 EXPERIMENTAL

The wafers were sawn from mono-crystalline, pseudo-squared silicon ingots with an HCT 500ED-8 wire-saw (Applied Materials Switzerland SA, Cheseaux-sur-Lausanne, Switzerland). Three cuts were made with different sets of sawing parameters. The parameters that were changed are the abrasive concentration in the slurry and the abrasive size distribution. The range of variation of these parameters is given in Table I. The parameters A correspond to the low SiC concentration in the slurry, parameters B to the high SiC concentration and parameters C to the fine abrasive cut. The abrasive sizes used correspond to the standard grit sizes F1200 and F800. The wire speed remained the same for all sawing experiments at 11.5 m/s, together with the slurry flow rate at 50 kg/min.

Table I: variation of the sawing parameters.

Parameter	A	B	C
Wire tension [N]	30	30	30
Table speed [µm/min]	450	450	450
Wire speed [m/s]	11.5	11.5	11.5
Concentration of SiC in the slurry [% vol]	15.1 %	30.9 %	23.8 %
Grit size	F800	F800	F1200
Grit size [µm]	6.5	6.5	3

Once sawn, the roughness of the wafers was measured with a contactless visible light profilometer (COTEC Altisurf 500) on 5.6 mm sampling lengths (in accordance with the norm ISO 4287) near the entrance of the wire into the ingot. In order to measure the cracks depth distribution, samples of a wafer were cut and embedded in a resin with a slight angle (about 5°) between the wafers surface and the surface of the resin. The samples were then polished and observed by visible light microscopy to measure the depth of the cracks. Finally, the wafers were broken on a ring-on-ring test bench according to a protocol described elsewhere [1, 6].

3 RESULTS

3.1 Bending tests

Three series of about 30 wafers were tested to determine their force-to-rupture. Figure 1 shows the Weibull plots of wafers sawn according to the parameters given in Table I. The corresponding Weibull parameters are given in Table II. As it seems that the closed-form equation giving the stress in the wafers from the applied force might not be valid [14], but to take into account the thickness difference between wafers cut with F800 and F1200 abrasives, the applied force divided by the square of the wafers thickness was used to represent the force-to-rupture.

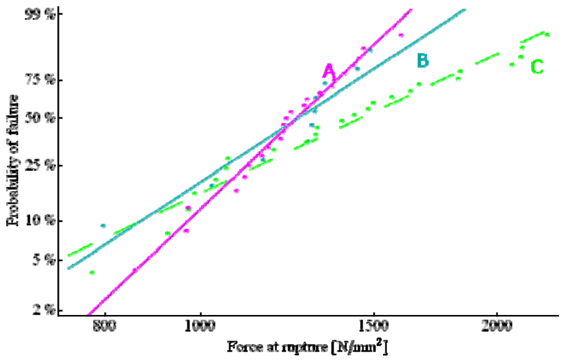

Figure 1: Weibull plots of wafers sawn with the sawing parameters given in Table I.

Table II: Weibull parameters for the three different sawing parameters given in Table I.

Parameter	A	B	C
Characteristic force [N/mm^2]	1314	1350	1604
Weibull module	7.4	5.1	3.7

From this plot (Fig. 1), it can be seen that the wafers sawn with a lower concentration of abrasive (curve A), despite having the lowest characteristic force of all three curves, has the narrowest distribution of fracture force. Ultimately, for a breakage rate that can be thought as acceptable in solar cells production – say 2 % breakage – these wafers can handle the highest force of all three sawing condition tested, as the force-to-rupture is higher for sawing parameters A than for parameter B and C up to a failure probability of respectively 49 % and 21 % .

3.2 Characteristic crack depth

The crack depth distribution obtained from optical microscopy observations could well be fitted into an exponential distribution: $p(d) = Ae^{-d/\gamma}$, where d is the depth, A is a pre-exponential constant and γ is the characteristic crack depth. From this type of distribution results a characteristic crack depth (γ), describing the rate at which the crack concentration decreases, or how deep the distribution goes. The values of the characteristic crack depth for the different cuts are given in Table III, together with roughness measurements.

3.3 Roughness

The roughness values are presented in Table III. It can be seen – as pointed out in reference [6] – that the average roughness and characteristic crack depth are correlated. Furthermore, characteristic cracks and roughness values of the cut A are closer to the values of the cut C (made with F1200) than of the cut B (made with F800), despite of the key role abrasive size plays in wafers quality [11].

Table III: Roughness and characteristic crack depth

Sawing parameters	A	B	C
Average roughness R_a [µm]	0.39	0.58	0.31
Maximal roughness R_z [µm]	4.72	8.04	3.41
Crack characteristic depth [µm]	6	9	5

4 DISCUSSION

All three measurements (roughness, crack depth distribution and fracture strength) converge in the direction that a lower abrasive concentration helps to have a better surface quality, for a given sawing speed. Despite the only partial description of the sawing process given by the rolling-indenting model [9, 10, 11], it can still give valuable insight about the reason for such results. Indeed, a lower roughness (or a shallower crack depth) implies that the load per particle, P_i, decreases (eqn. 1). Keeping in mind that the overall load has no influence on the load per particle, the two means to change this parameter are through the abrasive size distribution and the lubrication efficiency of the slurry (eqn. 4). As the lubricant stayed the same for all the experiments, only a difference in the load-bearing particles mean diameter ($L_{m,c}$) can explain a change in roughness between the sawing parameters A and B. The load-bearing particle mean diameter, which can be taken to be about twice the median diameter of the abrasive [9, 15], mainly depends on the distribution shape, but also, for a given distribution shape (like for the sawing parameters A and B), on the particle concentration in the slurry. Indeed, when the particle concentration decreases, a broader portion of the distribution is needed to sustain the total load. In short: for a given particle size distribution, $L_{m,c}$ decreases when the particle concentration is lowered, inducing a smaller load per particle, as stated by eqn. 4. This is corroborated by a previous study [6] showing that using smaller abrasive to saw wafers improved their breakage strength.

Taking the roughness values given in Table III, a value of α_1 consistent with [9] of 0.67 and the material properties of silicon (E=120 GPa, H=11 GPa, K_{1c}=0.82 MPa m$^{1/2}$) [16, 17], it is possible to compute the value of the load per particle with eqn. 1 (Table IV). It can be seen that decreasing the SiC concentration by a factor of two will decrease the load per particle by a factor of almost 3. Using a lower abrasive concentration will also improve the wafers mechanical strength, as it is expected from the rolling-indenting model and as it can be seen on fig. 1. The main asset of the cut A is that its fracture force distribution is narrower than the one of cut B. This implies that the deepest crack present – the one at the origin of the fracture – have a narrower depth distribution in the wafers from the cut A.

The broadness of the force-to-rupture is also the main difference between the cuts A and C. The Weibull curve of the cut C is very broad and, even if some wafers are very strong, others are very weak (even weaker than the wafers of the cut B). It indicates that even if, to some extent, a decrease of the abrasive size is beneficial, pushing the limits too much will induce less stability in the sawing process, in the sense that it yields very weak and very strong wafers. Unfortunately, this effect is not well described by the rolling-indenting model, as only one crack depth is taken into account and not a whole distribution. On the contrary, it can be seen in Fig. 1 that the broadness of the distribution has a critical impact on the wafers strength, as the cuts A and B have comparable median rupture strength.

Table IV: Indenting force per particle given by the rolling-indenting model according to the roughness measurement for the different sawing conditions

Cut	P_i [mN]
A	87
B	254
C	46

Finally, reducing the abrasive concentration has not only advantages. Indeed, by introducing eqn. 4 into eqn. 3, it can be seen that the sawing speed is dependant of the square root of $L_{m,c}$, thus diminishing the abrasive concentration, as it decreases the mean diameter of the load-bearing particles, lowers the sawing speed (all other parameters remaining otherwise constant). Or if the sawing speed is set constant, the overall pressure has to be higher, leading to an increased wear of the wire.

5 CONCLUSIONS

With this contribution, the impact of abrasive concentration on wafers surface quality was shown. Wafers were sawn at the same speed but with different concentration of F800 and F1200 abrasives and then analyzed. It results that wafers sawn with a lower abrasive concentration have a narrower distribution of the fracture force and a lower roughness. This finding can be explained with the rolling-indenting model, even if this model has some limits and might not apply fully to wire-sawing process [11]. Firstly, the broadness of the force at rupture distribution (or the broadness of the maximal crack depth) is not described – but plays a major role in the assessing the strength of wafers, as shown by the presented results. Secondly, even if – as predicted by the model – decreasing the abrasive size yields stronger wafers having a comparable breakage strength distribution broadness [6], this trend breaks when the abrasive size is too much decreased, as it will produce wafers having a very broad fracture force distribution, so that some wafers will be weaker than those cut with a coarser abrasive.

Finally, the use of the rolling-indenting model as a qualitative tool can yield useful insights into the sawing process but the results it provides must be used with caution, as illustrated with the wafers sawn with F1200 abrasive that – according to the model – should have been stronger than the other wafers but are in fact weaker due to a broad distribution of the force-to-rupture.

6 ACKNOWLEDGMENT

This project was supported by the Swiss Confederation's innovation promotion agency (CTI), Grant 7730.2 NMPP-NM.

7 REFERENCES

[1] K. Wasmer, A. Bidiville, J. Michler, C. Ballif, M. Van der Meer, P. Nasch; Proceedings of 22nd European Photovoltaic Solar Energy Conference (2007), 1135-1140.
[2] H. J. Möller; Phys. Stat. Sol. (a) 203, No. 4 (2006), 759-669.
[3] H. J. Möller; Adv. Eng. Mat. 6, No. 4 (2004), 501-513
[4] S. Schoenfelder, A. Bohne, J. Bagdahn; Proceedings of the 22nd European Photovoltaic Solar Energy Conference (2007), 1636-1640.
[5] C. Funke, O. Sciurova, S. Kaminski, W. Fütterer, H. J. Möller; ; Proceedings of the 21st European Photovoltaic Solar Energy Conference (2006), 171-175.
[6] A. Bidiville, K. Wasmer, J. Michler, C. Ballif, M. Van der Meer, P. Nasch; Proceedings of the 22nd European Photovoltaic Solar Energy Conference (2007), 1130-1134.
[7] C. Funke, O. Scourova, H. J. Möller, M. Stephan, K. J. Fröhlich, C. Seifert, A. Bachmann, A. Müller; Proceeding of the 19th European Photovoltaic Solar Energy Conference (2004), 1266-1269.
[8] C. Funke, O. Sciurova, O. Kiriyenko, H. J. Möller; Proceedings of the 20th European Photovoltaic Solar Energy Conference (2005), 1128-1131.
[9] M. Buijs, K. Korpel-van Houten, Wear 166 (1993), 237-245.
[10] M. Buijs, K. Korpel-van Houten, J. Mater. Sci. 28 (1993), 3014-3020.
[11] A. Bidiville, K. Wasmer, J. Michler, P. Nasch, M. Van der Meer, C. Ballif, to be published (2008).
[12] S. S. Chiang, D. B. Marshall, A. G. Evans; J. Appl. Phys. 53 (1982), 312-317.
[13] B. R. Lawn, A. G. Evans, D. B. Marshall; J. Am. Ceram. Soc. 63 (1980), 574-581.
[14] G. Coletti, N.J.C.M van der Borg, S. De Iuliis, C.J.J. Tool, L.J. Geerligs, Proceedings of the 21st European Photovoltaic Solar Energy Conference (2006), 1281-1284
[15] K. Philips, G.M. Crimes, T.R. Wilshaw; Wear 41 (1977), 327-350.
[16] D.R. Lide, ed. CRC Handbook of Chemistry and Physics. 86th ed. 2005-2006, CRC Press.
[17] J.F. Shackelford, W. Alexander, CRC Materials science and engineering handbook. 3rd ed. 2001: CRC Press.