IMPACT OF INDIVIDUAL PROCESS STEPS ON THE STABILITY OF SILICON SOLAR CELLS STUDIED WITH A SIMPLE MECHANICAL STABILITY TESTER

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ABSTRACT: One of the major obstructions during solar cell processing is the breakage of wafers due to initial or process induced cracks. A wafer breakage in a process line leads to time-consuming cleaning procedures and production loss. To investigate the impact of mechanical and thermal stresses of individual process steps on the stability of silicon wafers, a mechanical stability tester was designed and built. The fracture strength (i.e. the maximum force that leads to breaking of a wafer) was measured before and after each solar cell process step to detect changes in the mechanical stability of the partially processed solar cells. The investigation shows a strong influence of some process steps on the fracture strength. While alkaline etching and diffusion processes enhance the mechanical stability by approximately 11 %, mechanical edge isolation by sawing and contact formation lead to a reduction of approximately 10-30 % in the mechanical stability.

Keywords: Multi-Crystalline Silicon – 1 : Mechanical Properties – 2 : Manufacturing and Processing – 3

1 INTRODUCTION

The fabrication of silicon solar cells requires a certain mechanical wafer stability during each process step. The applied stress during the industrial solar cell process is related to two different effects. The first of these is mechanical stress, which reaches high values while handling, sawing and holding the wafer on a vacuum chuck during the printing process. Peak values are reached, if small grains of silicon dust lie between the wafer and the handling/chuck device, which produces leverage. The second stress type is of thermal nature. Diffusion and other high temperature furnace processes lead to wafer expansion and produce tensile and compressive forces in the material, which can result in cracks or propagation of existing cracks.

To investigate the influence of a process step on the mechanical stability, we stressed a large number of wafers using a mechanical twist test until breakage occurred. We then compared the breakage force with wafers having the same process history, excluding the relevant process steps. In this way, we measured the fracture strength, which is the maximum force applied to the wafer until breakage occurs.

Using this twist measurement, wafers with cracks could be sorted out. Implemented in production, this method could be used to reject as-cut wafers with macroscopic cracks before they enter the cell process. Within this work, no loss of wafers was observed during any processing step.

The major work in this paper was the investigation of the influence of the individual process step on the ability of multicrystalline silicon wafers to resist stress. The relevant process steps were the saw damage removal by alkaline etching, heating and diffusion treatment, edge isolation and the printing process were studied.

Detailed investigations were done to evaluate the influence of the amount of silicon removed by alkaline etching on the fracture strength. In addition, the notch generating effect of the edge isolation by sawing was studied, using the blade feed speed as a parameter. Figure 1 shows a SEM picture of a crack starting at a notch. Notches are important as they are known to be a major cause for generating flaws in material [1].

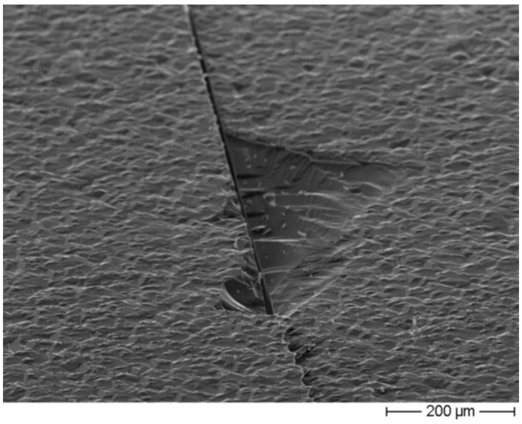

Figure1: Typical crack propagation due to stress, which was generated at a notch. The indentation was observed after the antireflection deposition.

2 SOLAR CELL PROCESS AND PREPARATION

The following industrial process steps were applied to the wafer material:

1. Alkaline defect etching,
2. $POCl_3$ diffusion (35 Ω/☐),
3. PECVD SiN_x deposition,
4. Edge isolation by sawing or plasma-etching,
5. Contact screen printing (Ag on front side, Al and Al/Ag pads on rear side)

We used BAYSIX wafer material of 330 µm thickness for the first experiment, in which the complete solar cell process was investigated (figure 3). 120 wafers entered the process sequence, with approximately 15 wafers measured (and therefore sorted due to wafer destruction) after each process step with the twist tester. The wafers were cut from the same column and randomly mixed to prevent misinterpretation of the results. This was necessary due to the fact that the mechanical properties of multicrystalline silicon are influenced by the size and orientation of the grains and also by the content of impurity atoms (especially carbon) [2,3]. In a previous experiment with wafers from another ingot, it was observed that the mechanical stability was 5-10 % lower for bottom ingot positions compared to top positions. We observed a decrease in the grain size from top to bottom. It was not possible to separate the effects of grain size and contamination on the mechanical stability.

The additional, more detailed investigations of the etching and sawing process (figures 4, 5 and 6) were carried out with BAYSIX wafers from another ingot, with a thickness of 330 µm (and 200 µm for the sawing process).

3 EXPERIMENTAL SETUP

A conventional method for testing the mechanical strength of thin ceramic samples is the biaxial flexure strength test [4,5,6]. The major disadvantage of this method for evaluating a fracture strength is the insensitivity to cracks located on the edge of a wafer, because the highest mechanical stress is generated by a ram pushing onto the center of the wafer. Particularly for multicrystalline wafers in a solar cell production line, microcracks at the edge of the wafer are believed to be the major cause for cell cracking.

A mechanical stability tester was designed that enables the application of the bending forces onto the corners of a square wafer, similar to the four point twisting tester of Chen [7]. The wafer lies horizontally on two fixed dowel pins, which support two diagonally opposing corners of the wafer. The measurement forces are applied by downward movement of two other pins pushing on the remaining two corners of the wafer. During the measurement, a force sensing device records the force, *F*, while the flexure (i.e. the displacement of the corners), *s*, is calculated from the number of steps of a stepping motor. The measuring routine is very fast; measurements up to 8 mm per second are possible. Figure 2 shows the setup.

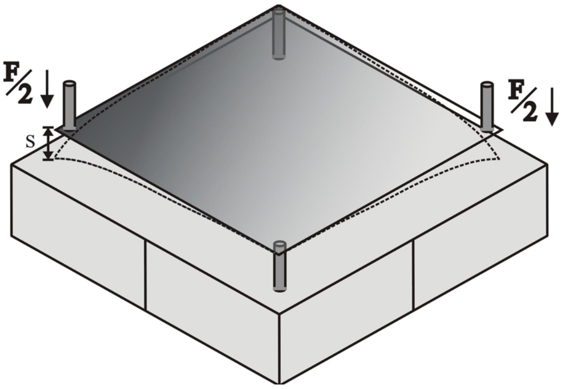

Figure 2: Four-point twisting of a wafer. The wafer is held by two dowel pins while it is stressed by downward bending of the two unsupported corners.

The two point twisting test stresses the entire wafer, therefore it is sensitive to flaws both in the internal wafer area and at the edges.

4 EXPERIMENTAL RESULTS

Figure 3 gives an overview of the change in mechanical stability of wafer material after the different processing steps. The stability increases after alkaline etching and phosphorous diffusion, whereas the AR deposition and mainly the edge isolation by sawing strongly decreases the ability to withstand mechanical stress.

All wafers underwent the same process sequence up to the studied process step. In the following sections the change of the fracture strength induced by the individual process steps (numbered as in figure 3) is described and some interpretation is given.

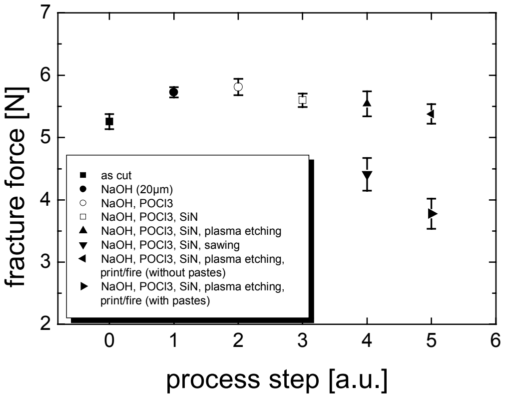

Figure 3: The effect of industrial solar cell processes on the mechanical stability of silicon wafer material.

4.1 ALKALINE ETCHING (Step 1)

An influence of different etching methods on the mechanical strength of the wafer is reported by several authors [5,7,8]. It is known that the breakage probability and the breakage force depend strongly on the wafer surface structure. The slicing of a mc-Si ingot into wafers by wire sawing produces a lot of saw damage on the wafer surfaces, which is removed by etching.

The wafers were etched in a 25 % NaOH solution at 80°C for 6 min. to remove an average of 20 µm thickness (10 µm per side), as determined by weighing the sample. An increase of the fracture strength of 9% was observed, which can be explained by the removal of the saw damaged as-cut wafer surface.

An additional experiment was done to investigate the effect of the etching time (i.e. etched thickness) on the mechanical stability. The absolute values of the fracture strength can not be compared with the experiment described above, because the wafers were taken from a different ingot. The results are given in figure 4 and 5.

Figure 4 shows an increase of the fracture strength with etched thickness up to 13 µm. SEM pictures showed a decrease in the amount of defects on the surface and on the edge areas after etching. An extended etching duration resulting in etched thicknesses over 20 µm (over 10 µm per side) lead to a step building between grains of different crystallographic orientation due to selective etching. The sharp edges of these steps may have acted as a starting point for crack propagation and therefore be mainly responsible for the observed reduction of the fracture strength for etched thicknesses over 20 µm. This effect is, of course, accompanied by a fracture strength reduction due to the thinning of the wafer.

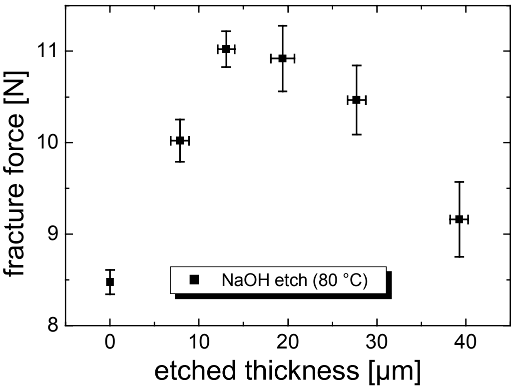

Figure 4: Dependence of the fracture strength on the amount of etched silicon (expressed as average thickness of the etched surfaces) by NaOH (80° C) etching. The maximum stability was reached with an etched thickness of between 13 and 19 µm.

The maximum flexure before breakage occurs is shown in figure 5. An increase of this maximum flexure can be seen up to an etched thickness of 28 µm. This increase is consistent with results published on monocrystalline silicon [5] and mainly caused by the thinning of the wafer. The subsequent decrease observed for an etched thickness of 38 µm can be explained by the step building, leading to a significant weakening of the wafer.

Experiments with several wafers (as cut) of different thicknesses, showed that the fracture strength changes only slightly with smaller thickness, whereas the flexure is strongly dependent on the thickness.

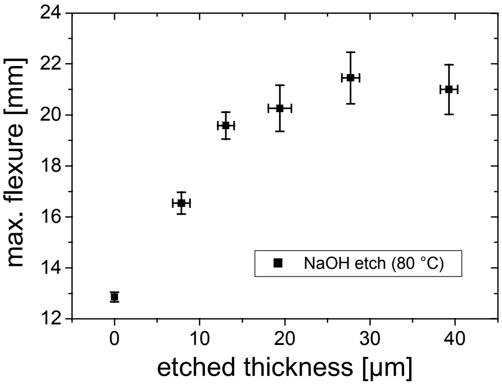

Figure 5: Dependence of the maximum flexure on NaOH (80° C) etched thickness. The largest displacement was found for an etched thickness of 28 µm.

4.2 $POCl_3$-DIFFUSION (Step 2)

No significant enhancement of the fracture strength (about 2 %, compared to 20 µm alkaline etched wafers) was measured after the $POCl_3$ diffusion, including an HF-dip for P-glass removal.

Yasutake [4] et al. reported an improvement in fracture strength after a temperature treatment in an oxygen environment for pre-cracked silicon wafers. It is believed that this improvement in mechanical strength is due to a healing effect at 700-1000 °C. The healing procedure is described as follows: Firstly the residual stress is released around crack areas and secondly, a rebonding of the crack surface due to a chemical reaction between the reaction gases and the silicon occurs. To verify these results in the special case of an $POCl_3$ atmosphere, further measurements would be necessary. Well defined crack formations are necessary, such as those produced with a Knoop diamond indentation method [9]. To exclude the influence of grains to the stability, these experiments should be performed with single crystal wafers. Franke et al [10] simulated the effect of thermo-mechanical stress during the diffusion process in the presence of a crack. He identified the unloading stage as the part of the process most likely to damage the mechanical strength. Tensile stress was produced, which opens cracks at the wafer edges or leads to crack propagation due to stress peaks at the crack tip.

4.3 SiN_x DEPOSITION (Step 3)

Within the antireflection coating process, a 60-80 nm layer of SiN_x is deposited onto one wafer surface. This process takes place at temperatures between 300 °C and 500 °C and therefore leads to internal stress, caused by different thermal coefficients of expansion (TCE) of silicon and SiN_x. This stress results in a small bending of the wafer and could generate, but more likely, open small existing cracks. Crack propagation starts to play an important role. After SiN_x deposition, a small reduction of the fracture strength (about 4 %) was measured.

4.4 EDGE ISOLATION (Step 4)

The edge isolation process is performed after SiN_x deposition. We used a single cutting blade (made of nickel containing diamond grains, thickness 80 µm) mounted on a DISCO sawing machine DAD341. The rotational speed was 10000 1/s, the blade diameter 76.2 mm and the feed speed 10 mm/s. In order to achieve comparable results all cells were sawed through, 1 mm to the edge, using the same blade. The results of the twist test were compared to cells that had the same processing history, but were plasma etched instead of being sawed.

The results of the experiment as displayed in figure 3 shows a loss of over 20 % in fracture strength, compared to the stability after antireflection coating deposition. SEM pictures revealed the cause for this weakening: a small number of notches could be seen along the cutted edge of the wafer, which were generated during the sawing process. It is expected, that hairline cracks were also generated, which would lead to crack propagation when a load acts on the wafer material.

In an additional experiment, the feed speed of the blade was varied between 5 and 40 mm per second. We used alkaline etched (80° C, 6 minutes) BAYSIX wafers of two different thicknesses (200 µm and 330 µm) for this investigation. Figure 6 shows the results, which were normalized to the fracture strength of alkaline etched wafers without edge isolation. The sawing process even for low feed speeds of 5 mm per second, effected very strongly the mechanical stability of the 330 µm wafers. For higher feed speeds a larger number of notches were observed with SEM. For the 200 µm material, 20 % of the sawed wafers broke with the lowest forces in the twist test (less than 1 N), indicating the fatal impact of the induced damage. We observed a greater decrease in stability for the 200 µm material at 20 mm/sec and 40 mm/sec compared to the 330 µm wafer.

Plasma etching showed no significant influence on the mechanical stability. The effect of different reactive gases and the plasma etching time will be investigated in further experiments.

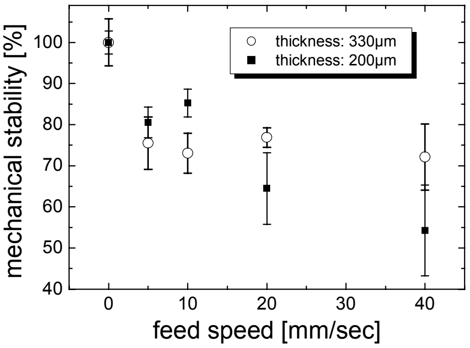

Figure 6: Influence of the saw feed speed on the mechanical stability of 200 µm and 330 µm thick BAYSIX wafers.

4.5 SCREEN PRINTING (Step 5)

The screen printing and contact firing are the most demanding process steps in terms of mechanical and thermal stresses. During the screen printing process, the clamping on a vacuum chuck and the squeegee exert considerable forces on the wafers, requiring a good support from below. Industrial screen printers use paper to minimise the number of foreign particles between the chuck and the wafer. In addition, an uneven wafer surface (warp) leads to insufficient support on the vacuum chuck and can therefore be a cause for stress and damage to the wafer.

After plasma etching the wafers were divided into two groups. The first was conventionally screen printed (silver paste on front side, aluminium paste and aluminium/silver pads on rear), dried and fired, whereas the second group was printed and fired without any pastes.

As can be seen in figure 3 (process step 5, upper symbol), the printing and firing without paste had negligible effect on the fracture strength (as seen from comparison with wafers after process step 4, upper symbol). Obviously the mechanical and thermal stresses of the printing and firing steps have no significant influence on the mechanical stability of the wafers.

The situation is different for group one. In this case, the fracture strength decreases by about 32 % (Step 5, lower symbol compared to the reference wafers of step 4, upper symbol in figure 3), which could be a major problem for module fabrication. We assume two principal reasons for this decrease. Firstly, the different thermal coefficients of silver, aluminium and silicon produce a certain bow, which stresses the wafer. If further stress is applied, these stresses add up and breakage occurs with much lower applied forces. The second assumed reason is the effect of the recrystallized silicon layer after firing the aluminiumn BSF. High dislocation densities and the rough interface to the brittle Al-Si eutectic alloy strongly influence the mechanical properties of the system.

5 CONCLUSION AND OUTLOOK

We demonstrated a fast method to investigate the mechanical stability of wafers with the 4 point twist tester. The obtained data provides us with the maximum force a wafer can withstand until breakage occurs. The displacement allows flexibility changes to be studied (provided the same force level is used).

A detailed mechanical study of the influence of each industrial solar cell process step on the mechanical stability has been performed. We observed a strong stability increase after the etching process. No influence of the edge isolation by plasma etching was observed, but the sawing process was found to strongly effect the fracture strength. The largest impact on the stability was was found to be the screen printing process, which yielded a strength reduction of over 30 %.

Integrated into production lines, the twist tester could be used to make a preselection prior to cell processing. This was first proposed by Chen [11]. Wafers already breaking under forces of 2 N are sure candidates for failure in the process line and could be identified and sorted out in less than 3 seconds using the twist tester. In further work the proof still has to be given, that this kind of testing has absolutely no influence on the stability of wafers without cracks.

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