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Wire-sawing processes: parametrical study and modeling

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ABSTRACT

Reducing the wafer breakage rate without changing the wafer thickness and sawing thinner wafers while maintaining constant breakage rate are two possibilities to decrease the costs of solar cells. They are similar in the sense that both require stronger wafers. To achieve this goal, it is important to gain insight into the wire-sawing process, its underlying defect creation mechanisms and the impact of sawing parameters on wafer strength. Consequently, a series of bricks were sawn with different slurry densities, wire tensions and feed rates, and the results were analyzed in terms of the wafer strength measured by bending tests. Roughness and wafer thickness were also measured. It is found that the strongest wafers were obtained by using a low abrasive volume fraction in the slurry, a low wire tension and a slow feed rate. From the analyses, we provide a qualitative interpretation of the effects of the processes at work in slurry-based wafering that explains, for instance, the wafer thickness and roughness variations. Based on physical arguments about the interaction between the wire, the silicon carbide particles and the silicon wafer, a semi-empirical model relating defect creation to the sawing parameters is developed. With this model, the wafer strength distribution can be predicted, thus simplifying optimization of the sawing process.

1. Introduction

Wire-sawing is the most common method to produce wafers for the photovoltaic industry. A wire-saw consists of a thin steel wire wound around wire-guides, forming a web of parallel wires (Fig. 1). Even though wires coated with diamond particles have started to be used industrially for sawing monocrystalline wafers, most wafers are cut with an abrasive slurry. The slurry, usually a suspension of silicon carbide (SiC) particles in polyethylene glycol (PEG), is poured on the wire web while the wire is driven through the web. The silicon block to be cut is then pushed through the web. The SiC particles carried by the wire wear the silicon away, hence sawing it into wafers. Due to the pressure for cost reduction over the last decade, wafer thicknesses have decreased from more than 300 to about 180 μm nowadays [1,2], while the wire diameter has also decreased. This has made the sawing process trickier, as thinner wafers and wires are more prone to breaking, and as a silicon brick is sawn into more wafers, the wear of the wire is more important. Therefore, research has been focused on producing stronger wafers, allowing thinner wafers to be sawn with reduced subsequent breakage, thus reducing silicon consumption [3,4].

At the wire-sawing stage, mechanical and geometrical parameters are useful to characterize the process. Whereas the electrical properties and the presence of precipitates are mostly determined by the solidification step, wire-sawing determines the wafer thickness, the wafer thickness variation, the roughness and the breakage stress. Another important aspect of wire-sawing is the breakage rate of wafers during or right after the cut. If, for a given sawing recipe, many wafers are broken before being processed into solar cells, this recipe cannot be deemed efficient as a large amount of high-quality material is lost. Although this aspect cannot be easily evaluated in a research environment as it requires sawing many full-load batches of wafers with the same recipe, it is reasonable to assume that if wafers are mechanically strong, fewer will break in the industrial process. To improve wafer quality, it is important to better understand the sawing process. Some groups rely on finite element simulations for insights into the interactions of the abrasive particle with the wire and the silicon block [5,6]. Such simulations focus on only a very small region (less than 200 μm in length), but still produce interesting results. However, these results depend largely on the assumptions made for the modeling: Wagner and Möller [5] applied a high contact force (5 mN per mm of wire, allegedly reflecting a moderate table speed) on the wire and showed that high contact force could be

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reached even if the wire-silicon distance was greater than the abrasive particle diameter, whereas Bierwisch et al. [6] showed that, in the so-called non-contact regime, the pressure of the abrasive particles on the silicon brick was low (in the range of the pressure applied by the wire, i.e. 0.15 N/mm^2) and homogeneously distributed around the wire. By contrast, they found that, in the so-called semi-contact regime, the force was located mainly at the top of the groove. Other researchers have used instrumented wire-saws to analyze the macroscopic forces present during the sawing process [7–9]. We have approached the problem from another perspective: by analyzing the wafer characteristics from a tribological point of view, we get insight into the material removal mechanisms and into the way the defects present in the wafers were created [10]. A study of the saw groove [11] showed that the sawing conditions are completely different at the top of the saw groove and on the sides (which later form the wafer surface, see inset in Fig. 1). It was also shown that, as the saw groove is thin and long, the sawing conditions change from the wire's entrance to its exit of the silicon brick. Similarly, it was demonstrated that the roughness and thickness variation is dependent of the SiC particle size. The larger the particle size, the larger are the roughness and thickness variation. A study of the effect of silicon debris confirmed these observations, as saw marks (abrupt thickness changes occurring in the form of lines parallel to the wire direction) first appeared at the wire exit side of the wafers when a concentration threshold is reached [10,12]. Furthermore, it was shown that small saw marks do not affect the wafer bending strength whereas large saw marks dramatically decrease it. It was demonstrated that roughness measurement is a good method for detecting saw marks, as roughness increases when saw marks are present. But when this increased roughness was smaller than the roughness at the wire entry side of the wafers, the wafers did not show a bending strength decrease.

In this contribution, the effect of the sawing parameters (abrasive volume fraction, wire tension and feed rate) on the wafer bending strength, the surface roughness and the wafer thickness is analyzed. With these results, a microscopic model of the sawing process is developed. It is in agreement with the observations made in our previously published papers [11,12] and allows for a better understanding of the sawing process. From this parametrical study, it is found that the strongest wafers are sawn with a low abrasive volume fraction, a low wire tension and a slow feed rate. Moreover, by looking at the impact of the sawing parameters on wafer characteristics such as the wafer thickness variation, the roughness variation and the breakage stress, insight into the sawing process is gained. This investigation also enables a better understanding of the particles' trajectories through the saw groove.

2. Material and experimental procedures

A modified HCT wire-saw, dedicated for research and development, was used to saw 125 × 125 mm^2 monocrystalline {100} silicon ingots with their edges along the <100> directions. The wire had a diameter of 140 μm and its pitch was 380 μm. The wire velocity was 11.5 m/s giving a total wire length of 230–250 km. Three size distributions of SiC abrasive were used: F600 (median size of 9.3 μm), F800 (median size of 6.5 μm) and a 1:1 mixture of F600 and F800, resulting in wafers with thicknesses of 200–220 μm. To keep the experiments at a reasonable price, the bricks had only a length of 50 mm so that about 120 wafers were produced per cut. However, no influence on the results is expected. The slurry flow was 112 kg/min. After ungluing the wafers from the sawing support, the wafers were cleaned with water and dried.

For each cut, the volume fraction of abrasive in the slurry, the wire tension and the sawing speed were investigated. Table 1 presents the sawing parameters used for each cut made with F800. The bricks cut with F600 and the mixture of F600 and F800 were cut according to parameters *A*–*C* in Table 1.

For each sawing condition, the thickness of ten wafers chosen randomly across the whole brick was measured as illustrated in Fig. 2.

Table 1
Sawing parameters for the cuts made with F800 abrasive. The volume fraction of abrasive in the slurry is V_{SiC}, the wire tension is T and the feed rate is f.

Cut	V_{SiC}	T [N]	f [μm/min]
A	0.261	30.0	450
B	0.236	30.0	450
C	0.211	30.0	450
D	0.211	25.2	378
E	0.211	30.0	378
F	0.211	25.2	450
G	0.211	21.2	450
H	0.211	21.2	378
I	0.236	30.0	378
J	0.236	25.2	378
K	0.236	25.2	450
L	0.236	21.2	450
M	0.236	21.2	378

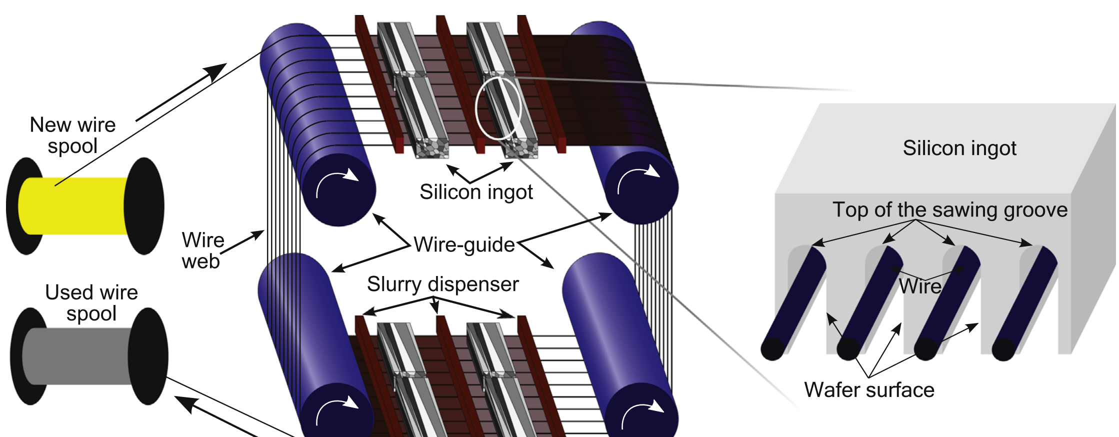

Fig. 1. Simplified view of a wire-saw. Silicon bricks are glued onto holders (not shown) and pushed progressively through the wire web as the wire is running and slurry is poured onto the web. The inset on the right shows a schematic view of the wire entering the silicon ingot. The created grooves separate the wafers at the end of the cut.