ABSTRACT: The objective of this work has been to identify the root cause of the reduced etch rate of fixed abrasive sawing (FAS) cut wafers during damage etching. The etch rate in alkaline solutions was measured as a function of time, temperature and different pre-cleaning processes, both for FAS and standard slurry wafers. The results showed a maximum etch rate for KOH concentrations around 20-30 wt%. The etch rate of FAS wafers was lower compared to slurry wafers during the initial 5-10 minutes of etching, dependent upon KOH concentration and temperature. In order to characterize the wafer surface, scanning electron microscopy (SEM), transmission electron microscopy (TEM), atomic force microscopy (AFM), as well as reflectance measurements were used. By comparing the cross sections of the surface structure of as cut slurry and as cut FAS wafers, both an amorphous silicon layer and a defect layer were observed, but is concluded to not limiting initial higher etch rate. Furthermore during the initial stage of damage etching inverted square pillars were always formed. The walls of the pillars were constructed by the fast etching [110] planes. The depth of the pillars is found to be shallower for FAS cut wafers due to initially lower surface roughness. Therefore, the surface area exposed for the damage etch solution is larger for the slurry cut wafers, which explains the larger etching rate for the slurry cut wafers during the initial stage of the etching.

Keywords: c-Si, sawing, etching, characterisation

1 INTRODUCTION

The diamond wire or fixed abrasive sawing (FAS) technique has a potential for commercial production of silicon wafers, as it can increase productivity for example by a factor of two or more in terms of table feed speed [1]. However, the introduction of FAS wafers into solar cell production lines has revealed that under certain circumstances, modifications to the etching protocol or etching time might be required due to fundamental differences in the surface structure [2]. The reduced etch rate observed for FAS wafers may be due to masking of the surface either by organic residues, amorphous silicon or by a silicon oxide layer.

In a previous study [3], the surface structure of both slurry and FAS wafers etched under the same conditions were studied. The presence of micro cracks distributed inward from the wafer surface as deep as up to 4 µm were observed for the slurry wafers. Contrarily, micro cracks were not found to be present for the FAS cut wafers. Furthermore, during the initial part of the etching, square inverted pillars were formed for both types of wafers. The inverted pillars were initially deeper for the slurry cut wafers due to larger surface damage during sawing. The main etch directions were <100> and <110> as shown in Figure 1.

The objective of this work has been to identify the root cause of the reduced etch rate during damage etching of FAS wafers, whether it is surface structure related, defect related, due an oxide layer present on the surface, or due to organic residuals.

2 METHODS AND EXPERIMENTAL SETUP

180 µm thick 5-inch semi-square Cz monocrystalline silicon wafers made by diamond wire sawing and by standard slurry sawing were studied as function of etching time. The average thickness of the wafers before and after etching was calculated by measuring the weight of the wafer, given the density of crystalline silicon wafers and geometry.

Figure 1: Sketch of a 5-inch semi-square Cz-wafer showing the orientation of the inverted pillars.

The etch rate in alkaline solutions was measured as a function of time, temperature and different pre-cleaning processes, both for FAS and standard slurry wafers. Alkaline solutions of KOH in the concentration range from 10-47 wt% and temperatures from 50-75°C were used. The wafers were etched both with and without pre-cleaning steps. In case of pre-cleaning, HF acid was used to remove a possible masking oxide layer, whereas high temperature annealing followed by HF acid etching was used to remove organic residuals.

Cross-sectional TEM samples were prepared by grinding and ion-milling. Reflectance measurements were carried out using a fiber-based, optical arrangement consisting of a broadband light source (Mikropack DH-2000), an integrating sphere (Mikropack ISP-30-6-R), and a spectrometer (Ocean Optics HR2000+). The weighted average reflectance in the wavelength range from 280-1000 nm was calculated, based on the Reference Solar spectral Irradiance for Air Mass 1.5. The surface structure was studied by a Hitachi S-4800 scanning electron microscope (SEM), a 200 kV JEOL
2010F transmission electron microscopy (TEM) as well as an atomic force microscope (AFM) from Surface Imaging Systems.

3 RESULTS AND DISCUSSIONS

3.1 Etching rates
Figure 2 shows the thickness reduction and surface reflectance for the slurry cut wafers as function of etch time for different concentrations of KOH at 75°C.

Initially, there is a high and non-linear etching rate, which subsequently decreases and becomes constant after a period of about 5-10 minutes. The largest etch rate is obtained for KOH concentrations around 20-30%, in correspondence with previous reports [4]. The initial drop in reflectance is due to openings of micro cracks [3], which enhances the surface texturing.

Figure 3 shows the thickness reduction and surface reflectance for the FAS cut wafers as function of etch time for different concentrations of KOH at 75°C. The etch rate for the FAS cut wafers shows the same behaviour as the slurry cut wafers. The initial reduction of the surface reflectance is not so pronounced since micro cracks are not present on the surface.

By comparing the thickness reduction of slurry cut and FAS cut wafers, the etch rate is lower for the FAS cut wafers in the initial period of 5-10 minutes. This is elucidated in Figure 4, in which the thickness reduction of both slurry and FAS cut wafers for KOH concentrations of 30% and 47% are plotted. For an etch time longer than approximately 10 minutes the etch rate is the same for both types of wafers.

Figure 4: Wafer thickness reduction for slurry and FAS cut wafers as function of etch time for different concentrations of KOH at 75°C

3.2 TEM study
TEM was used to investigate the surface structure for both as cut slurry and as cut FAS wafers. Figure 5 shows a cross section of a slurry cut surface, showing an outer layer of amorphous Si (a-Si) with a typical thickness of 20-40 nm. Underneath the amorphous layer, a 300-600 nm thick defective region can be observed. The defects seem mostly to be twinning, and they are located in the (111) planes.

Figure 5: TEM images and diffraction pattern of as cut slurry wafer, showing defects at the surface as well as an amorphous silicon layer

Figure 6 shows a TEM image and diffraction pattern of an as cut FAS wafer. This sample has a surface with low surface roughness, but contains a high density of defects close to the surface. Most defects are located in an 800 nm layer at the surface, but some are located as deep as 2000 nm. Many of the defects seem to be twinning also here. Moreover, there is a 40-150 nm thick amorphous Si layer present at the surface.

By comparing the cross sections of the surface structure of as cut slurry and as cut FAS wafers, both the amorphous layer and the defect layer are 2-3 times in average thicker for the FAS cut wafers. This indicates higher stresses during FAS sawing process. Based on the measured etch rate at the initial stage of the etch process, the amorphous silicon layer observed by TEM is etched
away during first 2-5 seconds and is thus not the cause of the reduced etch rate during the initial period.

**Figure 6:** TEM image and diffraction pattern of as cut FAS wafer, showing defects at the surface as well as an amorphous silicon layer

3.3 Pre-treatments

Figure 7 shows the etch rate of a FAS cut wafer after different pre-treatments. Only insignificant changes in the etch rate were observed when pre-cleaning processes were performed, which suggests that there is no masking layer of silicon oxide or organic residuals present at the surface. This finding was also confirmed by TEM investigations.

**Figure 7:** Wafer thickness reduction for the FAS cut wafer as function of etch time for different pre-treatments

3.4 Surface structure

During the initial stage of damage etching the inverted square pillars were formed for both slurry cut and FAS cut wafers for all alkaline solutions used in this study (10-47 wt% KOH). Figure 8 shows an example of a FAS wafer etched for 1 minute. The walls of the pillars are constructed by the $\{110\}$ planes and the bottom is constructed by the $(001)$ plane.

As shown in the Figure 9 the total exposed surface area of the $(001)$ plane is approximately equal for both FAS and slurry wafers.

However the depth of the inverted square pillars is shallower for FAS cut wafers due to initially lower surface roughness. Therefore, the surface area of the $\{110\}$ planes exposed for the damage etch solution is larger for the slurry cut wafers, which explains the larger etching rate for the slurry cut wafers during the initial stage of the etching process compared to that of the FAS cut wafers.

**Figure 8:** 15 x 15 μm AFM image of a FAS cut wafer etched for 1 minute in 47% KOH at 75°C.

**Figure 9:** SEM images of a slurry (upper) and FAS (lower) cut wafer etched for 5 minutes in 30% KOH at 65°C. The inverted square pyramids are expanding as function of the etch time. It has also been observed that the deeper pillars are suppressing the shallower pillars. Thus, for prolonged etching times the surface is only constructed of a few nearly vanished pillars as shown in Figure 10.

By measuring the expansion of the inverted pillars as a function of etching time, the etching rate in $\langle 110 \rangle$ direction can be calculated. Similarly the etch rate in $\langle 001 \rangle$ direction can be calculated in the region where the etch rate is constant, thus ignoring the none-linear region
during the initial stage where a substantial amount of the etching in <110> direction contributes to thickness reduction.

By using the described methods above, the etch rate in a 30 wt% KOH solution at 75°C in the <001> and <110> direction has been calculated to be 1.15 and 2.3 µm/min, respectively. In other words, the etch rate in the <110> direction is twice as fast as in the <001>. This even further strengthens the theory explaining the faster etch rate for slurry wafers due to presence of larger surface area in form of {110}.

![SEM image of a slurry cut wafer etched for 20 minutes in 30% KOH at 75 °C](image)

**Figure 10:** SEM image of a slurry cut wafer etched for 20 minutes in 30% KOH at 75 °C

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5 REFERENCES


