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Effect of mechanical surface damage on Silicon wafer strength

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Abstract

Solar power generation using polycrystalline silicon wafers has been rapidly growing in recent years. As a result, it is required to understand the strength characteristics of polycrystalline silicon wafers in order to enhance their quality. Scratches and material defects should be taken into consideration when strength characteristics of polycrystalline silicon are evaluated, since it is a brittle material. In this paper, bending strength of polycrystalline silicon wafers for solar cells were measured, and evaluation regarding the cause of different strength values, which depend on manufacturing conditions of the wafer, was conducted based on fracture mechanics. Residual stress measurements using Raman spectroscopic and observation with TEM (Transmission Electron Microscope) were also conducted. The results clarified the existence of numerous cracks on the wafer surface that are assumed to be generated during slicing process. Thus, it was confirmed that wafer strength depends on the level of machining damage in slicing process. We can establish high reliability for PV modules as a result of modifying the slicing conditions to minimize the mechanical surface damage on wafers and increase the wafer strength.

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Keywords: Crystalline silicon; Fracture strength; Slicing process; Raman spectroscopic; Crack; Residual stress

1. Introduction

In recent years, photovoltaic power generation has been extending all over the world in consideration to environmental problems. Polycrystalline silicon is widely used since it is cost effective, and this tendency is expected to continue [1].It is necessary to understand the strength characteristics of silicon

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wafers in order to enhance the quality (ex. the thinner the wafer, reliability for a longer lifetime) of PV modules.

Crystalline silicon is a brittle material and has high notch sensitivity. Therefore, crack evaluation is indispensable in its quantitative strength assessment, and especially attention should be paid to manufacturing damage in the slicing process from ingot to wafer production. In the past, there were some reports of strength evaluation of silicon wafer for integrated circuits [2]. Because the manufacturing process of wafers for solar cells is not the same as for integrated circuits it needed a single purpose evaluation for polycrystalline silicon. Especially polycrystalline silicon has many crystal grain boundaries and deficiencies in the crystal structure. It means that the clarification of a strength factor is important for the polycrystalline silicon.

This paper presents the effects of surface damage on the silicon wafer strength. The polycrystalline silicon wafers were manufactured by a wire saw. It is known that the affected layer of the surface occurs when the ingot is sliced (Fig 1). First we measured strength and fracture toughness, so that the strength of damaged polycrystalline silicon wafer was evaluated based on fracture mechanics assuming the damaged layer as potential cracks on the wafer surface. For evaluation of surface damage, microscopic observation by using both a transmission electron microscope (TEM) and Raman spectroscopic were conducted for different strength polycrystalline silicon wafers.

2. Evaluation of Strength Characteristics

2.1. Test Samples

A polycrystalline silicon wafer for this study is shown in Fig 2. The sample was manufactured by slicing an ingot into 150mm x 150mm square wafers of 200μm to 300μm thickness using a wire saw, and then cutting 10mm widths using diamond dicing. The cut surface by diamond dicing is shown in Fig 3. The cut surface is smoother compared with the wafer surface and it was confirmed that fracture did not initiate from the cut surface. Three types of test pieces were prepared: samples are manufactured by different slicing conditions. Sample A and B were made from the same ingot, but sample C was made from the different ingot.

2.2. Bending Strength Test

A four point bending test was conducted to measure the tensile strength by using a tensile testing machine (Fig 4). A four point bending test can get more accurate results than a three point bending test and ring-on-ring test. Because it can apply high stress over a large area, there is little displacement from the high stress point to the break point. Bending strength σ was calculated using the following equation,

$$\sigma = \frac{3F}{bt^2}\frac{(L_1 - L_2)}{2} \tag{1}$$

Where, F is the applied load, b is the width of the sample, t is the thickness, L_1 is the larger span, L_2 is the smaller span.

Fig 5 shows measured results of bending strength. Samples A, B, and C have different bending strengths. Especially, the bending strength of samples A and C are different value although samples A and C are made from the same ingot. It suggests that the difference in bending strength is not caused by the difference in ingots but caused by slicing damage on the surface.

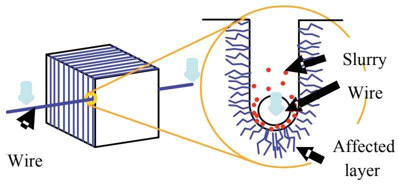

Fig. 1. Image of affected layer when wire slicing

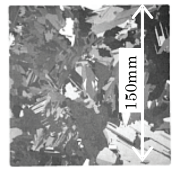

Fig. 2. silicon wafer

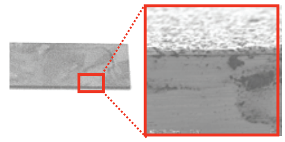
Fig. 3. Test piece

Fig. 4. Four-point bending test

2.3. Fracture Toughness Test

In order to evaluate the effect of surface cracks due to machining damage, fracture toughness (K_{IC}) of polycrystalline silicon wafers was measured by controlled surface flaws (CSF) method [3]. Same test piece for bending strength test was used. Knoop indenter was pressed on the center of the test piece with its longitudinal axis set to be perpendicular to the longitudinal direction of the test piece. Indentation load was set at 5N and 10N. Sample A and sample B from different ingots were used. Then, the four point bending test was conducted by loading a tensile stress on the surface where the Knoop indentation had been applied. K_{IC} was calculated by following equation for stress intensity factor,

$$K_{IC} = F\sigma_B\sqrt{\pi a} \tag{2}$$

where σ_B is the fracture stress obtained from the bending strength test, a is the crack depth due to Knoop indentation, and F is a correction factor, respectively. Semi-elliptic crack due to Knoop indentation can be seen and F is determined from the following equation [3].

$$F=1.1359-0.3929\mu-0.3440\mu^2-0.2613\mu^3+\lambda(-1.5184+0.4178\mu+0.7846\mu^2-0.6329\mu^3)$$
$$+\lambda^2(4.3721-13.9152\mu+16.2550\mu^2-6.4894\mu^3)+\lambda3(-3.9502+12.5334\mu-14.6137\mu^2+5.8110\mu^3)$$

and

$$\mu=d/w,\ \lambda=d/t \tag{3}$$

Where, *d* is crack depth, *w* is a half crack width, and *t* is thickness of the test piece.

Although silicon is an anisotropic material, measured K_{IC} for different crystal orientations are distributed from 1.11±0.07 to 1.18±0.03 MPa ・$m^{0.5}$ according to the previous investigation [3], which is little affected by crystal orientation. Therefore, crystal orientation was not taken into consideration in this investigation.

Fig 6 shows measured results of fracture toughness (K_{IC}). Fig 7 shows the fracture surface. Sample A and B have almost same K_{IC} values. Though the bending strength of sample A and B is different they have almost same the K_{IC} value. Therefore, it can be considered that the difference in bending strength is caused by slicing damage on the surface as well.

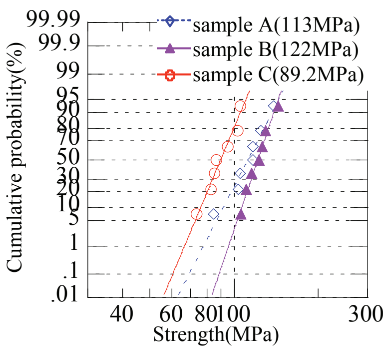

Fig. 5. Results of strength measurement

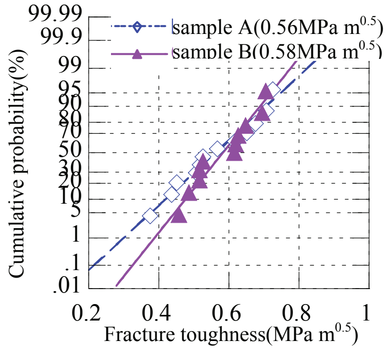

Fig. 6. Results of fracture toughness measurement

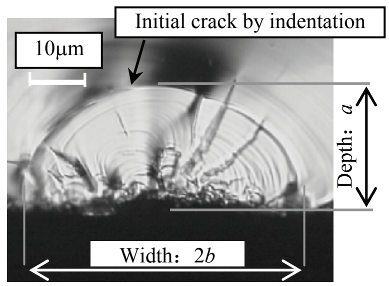

Fig. 7. Controlled flaw

2.4. Strength Test for the Wafer Eliminated Damage

We manufactured a sample whose surface damage was eliminated then we conducted a bending strength test described in chapter 2.2. Sample D was manufactured from sample A by surface polishing and reducing 20% of its thickness. Fig 8 shows the polished sample compared with an unpolished sample.

The results are shown in Fig 9. The bending strength of the sample D is about three times greater than that of sample A in the initial condition, confirming the big contribution of surface cracks to the strength deterioration of polycrystalline silicon wafers

Therefore this result shows that the crystal grain boundary and deficiency of the crystal structure of polycrystalline silicon does not affect the strength of the wafer at least under 300MPa.

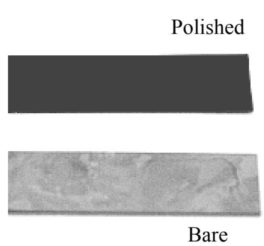

Fig. 8. Polished sample

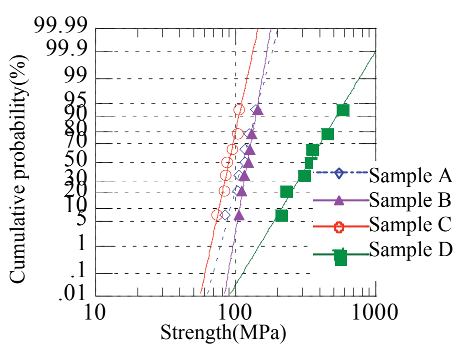

Fig. 9. Results of strength measurement

3. Evaluation of Surface Damage

3.1. Surface Observation by TEM

Surface observation by TEM was conducted for sample B and C in order to investigate the level of surface damage. The sample for the observation was cut by Focused Ion Beam (FIB) to observe the thickness direction of the wafers. Average sample thickness was 0.25 µm, and length was 20 µm.

Results of TEM observation is shown in Fig 10 and Fig 11 at the same scale. In spite of a narrow observation surface of a couple of micron square meters, some interference fringes that indicated crack existence were observed in both samples. Furthermore, the crack in sample C is apparently larger than that of sample B, which indicates a correlation with bending strength.

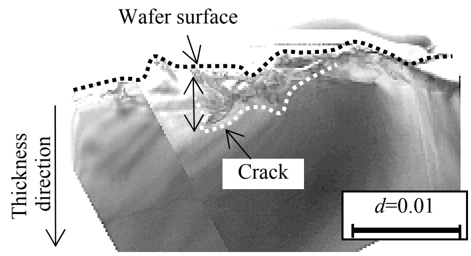

Fig. 10. TEM image of cross section (sample B)

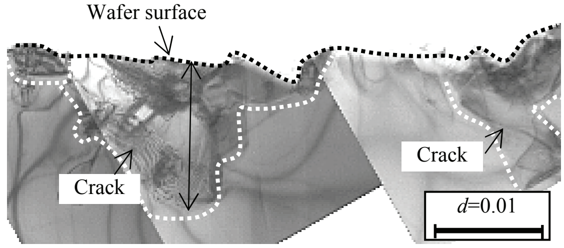

Fig. 11. TEM image of cross section (sample C)

3.2. Residual Stress Measurement using a Raman Spectroscopic

Observed area by TEM is 10^{-8} times smaller compared to test piece area of strength sample. Therefore, evaluation of residual stress distribution using Raman spectroscopic was tried in order to cover a wide surface range. Raman spectroscopic analysis can measure residual stress as mechanical damage, and evaluate the deterioration of the crystal structure [5]. Total value of three axis principal stress is measured as a positive value of compressive stress in the Raman spectroscopic. Residual stress from the surface to the thickness direction was measured in the wide cross section.

Measured residual stress for sample A and D are shown in Fig 12. In Fig. 12 axis of ordinate shows residual stress and abscissa is a distance from the surface normalized by sample A thickness. The compressive residual stress near the surface of sample A is high, while that of sample D is low due to mirror polishing. Therefore, it was confirmed that damage by machining causes the residual stress.

Bending strength of sample D is higher while its compressive residual stress near the surface is low. It can be considered that the singular stress field caused by the crack chapter has a greater effect on bending strength than the enhanced strength caused by the compressive residual stress.

The residual stress of samples A, B, and C are shown in Fig 13 as a log-log plot. Residual stress converges to some extent as the distance from the surface becomes greater. It was confirmed from samples A, B, and C that surface machining damage has an effect on the wafer bending strength because the bending strength reduces as the residual stress increases.

Focusing on the residual stress near the surface of samples A, B, and C described in Fig 13, it can be assumed that transitions or cracks exist due to machining damage and that crystal structure is deteriorated because the residual stress has a large variation. The maximum residual stress had a tendency to saturate near 500 MPa for all samples, clarifying the existence of a residual stress threshold. This phenomenon is probably due to the nonlinearity of crystal silicon such as the occurrence of transitions caused by shear stresses or the occurrence of cracks caused by the destruction of crystals. These transitions or cracks are supposed to work as potential cracks [6] but work as strength parameters instead.

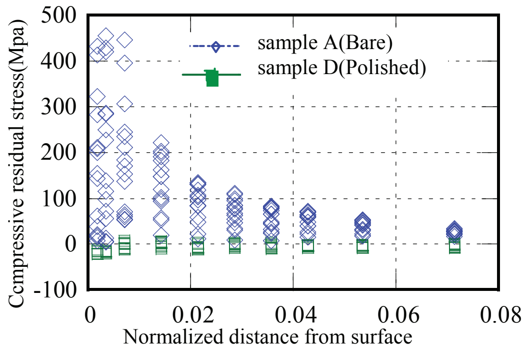

Fig. 12. Results of Raman spectroscopic (Linear scale)

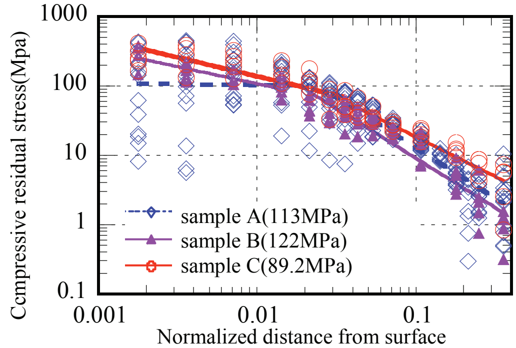

Fig. 13. Results of Raman spectroscopic (Log scale)

4. Conclusions

Investigations on surface damage and strength measurement of photovoltaic polycrystalline silicon wafers were conducted and the following results were obtained:

(1) According to the bending strength test and the fracture toughness test, surface damage due to machining was found to affect bending strength. The bending strength of the samples whose machining damage was modified by mirror polishing was about three times higher than that of samples in the initial condition. Also it was found that the crystal grain boundary and deficiency of the crystal structure of polycrystalline silicon does not have an effect on the strength of the wafer at least under 300MPa.

(2) Surface observation by TEM clarified numerous cracks on wafer surface. It also showed that cracks on a small strength sample have a strength that is apparently larger than that of a large strength sample, which indicates correlation with bending strength.

(3) From surface observation by Raman spectroscopic it was confirmed that damage by machining caused the residual stress.

The results clarified the existence of numerous cracks on the wafer surface that are assumed to be generated during the slicing process. Thus, it was confirmed that wafer strength depends on the level of machining damage in the slicing process. We can predict higher reliability for PV modules as a result of modifying the slicing conditions so as to reduce the mechanical surface damage on wafers and thereby increase the wafer strength.

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