EFFECT OF PRODUCTION PROCESSES ON THE FRACTURE STRENGTH OF SILICON SOLAR CELLS

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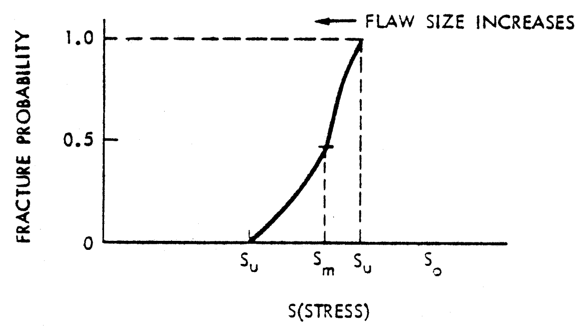
ABSTRACT

Fracture of Czochralski silicon wafers during processing is an important factor in solar cell yield and cost. A fracture-mechanics test and analysis program was developed to evaluate fracture strength changes in the in-process wafer-to-cell processing at different stages on a manufacturer's production line. The strength data were described by Weibull statistical analysis and can be interpreted with the surface-flaw distribution of each of the process steps.

INTRODUCTION

The cracking cell is one of the major causes of solar-panel rejection and failure (1, 2). Cracking of silicon solar cells during field service and testing is believed to result from the extension of critical preexisting flaws under stress. Such flaws, probably generated during silicon wafering and cell processing and handling, may therefore limit the mechanical strength of silicon solar cells. This information emphasizes the importance of the mechanical strength data on silicon solar cells as functions of manufacturing process steps. The data resulting from such testing could be used by manufacturers of solar cells to enhance production yields and to improve cell reliability and durability, and would reduce cell cost and support the development of automated production.

Strength data resulting from studies of brittle materials typically show a great deal of scatter. Thus the conventional method of representing observed quantities using the arithmetic mean and its standard deviation may not show a significant characteristic of strength distribution. A statistical method commonly used to describe the strength of brittle materials is that given by Weibull (3, 4). In Weibull analysis it is assumed that fracture at the most critical flaw under a given stress distribution leads to total failure. By this method, the typical Weibull distribution of strength data of brittle materials can be shown in an equation to relate fracture probability, G, with stress, S. This is plotted in Figure 1. From this equation it is apparent that the larger the surface area of the material under bending stress, the lower the strength distribution obtained from the test. This phenomenon can be interpreted to mean that the larger the surface area under stress, the greater the probability of finding a larger flaw. Therefore, strength data of brittle material depends on both the test sample size and



$$\text{FRACTURE PROBABILITY } G = 1 - \exp\left[- \int_A \left(\frac{S - S_u}{S_o} \right)^m dA \right] \qquad (1)$$

where

S_u =	Stress below which none will fail
$S_u + S_o$ =	Stress above which all will fail
S =	Stress of interest
m =	Weibull Modulus (Related to slope of plot)
S_m =	S at 0.5 G, $S_m \approx S_{avg}$

Figure 1. Typical Weibull Distribution (Weakest Link Statistics) of Strength Data of Brittle Material

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the test method in which the surface area of the sample is stressed.

It is important to note that the Weibull modulus, m, which describes the slope of the curve, is related to flaw-size distribution in a material. The smaller m value indicates greater distribution of flaws and greater scatter of the strength data, and shows a smaller slope on the Weibull curve.

The purpose of this paper is to address the results of the fracture strength tests of silicon solar cell samples from various steps of wafer-to-cell processing on a typical manufacturer's production line.

The Weibull plot will be used to display and interpret the general characteristics of strength on silicon solar cells.

EXPERIMENTAL PROCEDURES

Specimens

Typical solar cells produced by several manufacturers were considered for use in this effort. Those selected for study were the products of a specific manufacturer* with processing facilities for the complete beginning-to-end production of solar cells.

An attempt was made to obtain a representative sample at each significant step in the production process.

The test specimens included a series of wafer and cell samples 76 mm (3 in.) in diameter from Czochraski ingot at several process steps** as follows:

SPECIMENS	APPROX. THICKNESS (μm)
As-cut wafers (multi-wire slurry wafering)	440
Chemically polished wafers***	380
As-cut edge-rounded wafers	440
Texture-etched wafers	420
Mesa-etched and antireflection (AR) coated wafers	430
Pre-ohmic cells	430
Completed (metallized) cells	550

* Motorola Inc., Semiconductor Division, Phoenix, AZ.

** Processing procedures are proprietary information.

***Chemical polishing is not commonly used in cell processing. These wafer specimens were made from as-cut wafers (no edge rounding) for strength evaluation only. All other wafers and cells of subsequent processes were made from edge-rounded wafers.

The thickness of each cell sample was measured before the test for fracture-strength calculation.

The properties of the silicon wafers are: (100) orientation: boron doped, P-type; resistivity ranging from 0.8 to 2.0 ohm-cm.

Testing Method

Conventional methods for testing the strength of thin ceramic samples are the modulus-of-rupture (MOR) test (Figure 2) and biaxial flexure strength test (5, 6) (Figure 3). However, in the modulus-of-rupture test only portions of the sample and edges of the sample are stressed; in the biaxial strength test the maximally stressed surface area is confined within the central region of the specimen. The latter test method does not evaluate the condition of the specimen's edge. Edge flaws are believed to be the major cause of cell cracking.

A specially designed test method known as four-point twisting has been evaluated (7, 8) and appears to be useful in testing the strength of silicon solar cells. The cell sample is loaded by four equal forces, evenly spaced, at its edge, normal to its surface. The forces are supplied upward on two diametrically opposite points, downward on the other two (Figure 4). The maximum twist stress τ_s for a circular solar cell under four-point twisting can be calculated by an equation;

$$\tau_s = \frac{3P}{2t^2} \qquad (2)$$

where t is the thickness of the cell, and P is the total fracture force.

The four-point twisting test not only has a simple and symmetrical loading configuration, but also has self-alignment and is easy to perform. In addition, it stresses the entire wafer specimen, including edges and internal area.

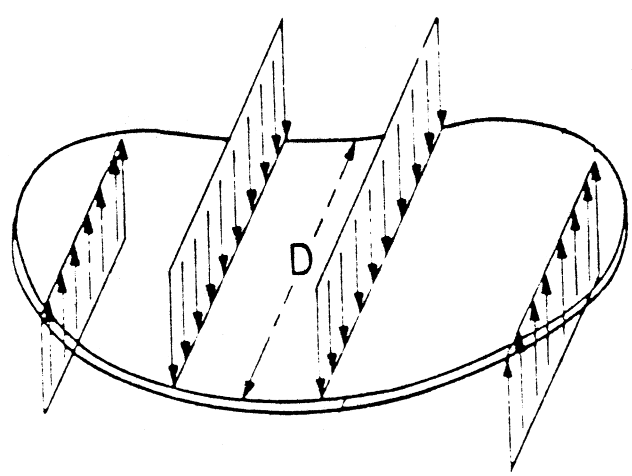


Figure 2. The Modulus of Rupture Test

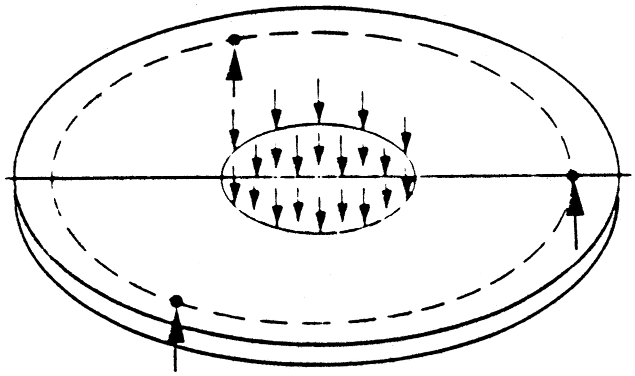


Figure 3. Biaxial Flexure Strength Test

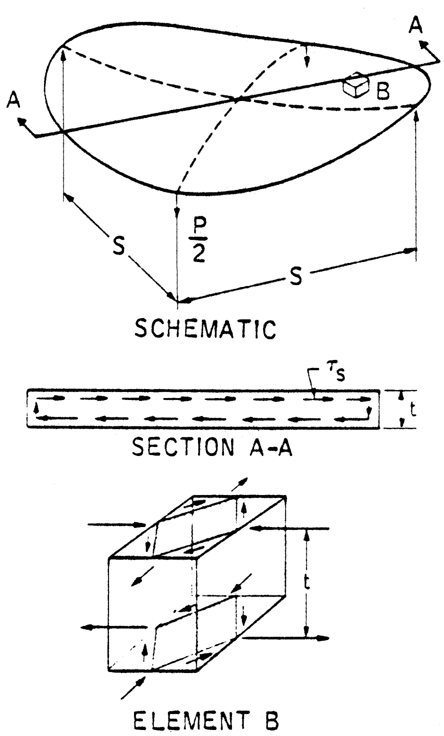


Figure 4. Four-point Twisting of a Solar Cell

Four-point twisting is therefore used for testing the mechanical strength of silicon solar wafers and cells at several processing steps.

TESTING APPARATUS

The four-point twist jig for solar cells is shown in Figure 5. During the test, two dowel pins 180° apart on the bottom disk act upwards while the other two on the upper disk, 90° from the first two, act downwards to give a shear stress at 45° in the cell specimen, as shown in

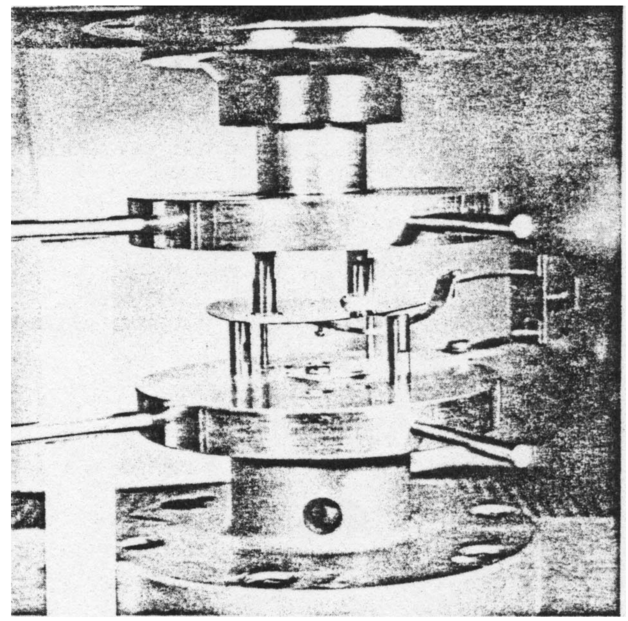


Figure 5. Solar Cell Four-point Twist Jig

Figure 4. A teflon washer (12.7 mm OD, 1.7 mm thick) was used at the contact point of each dowel pin to minimize the stress concentration. These four dowel pins were designed in a 63.5 mm (2.5 in.) dia circle.

The load was applied by an Instron Testing Machine* with loading rate 0.1 in./min and chart speed 2 in./min.

RESULTS AND DISCUSSIONS

The twist strengths of silicon wafer samples from several cell process steps are given in Weibull distribution plots and are compared in Figures 6 and 7. The following observations can be made from the data:

1. The twist strengths of both as-cut and edge-rounded wafers at 50% fracture probability are the same: 93 MN/m^2. The Weibull distributions for these two types of wafers are also identical. The mechanical edge rounding method produces no increase in the strength of silicon wafers. The manufacturer has reported that edge rounding has been used to reduce cell cracking of etched cells during processing and handling. No data on etched cells with unrounded edge are available for comparison.

2. The twist strength of chemically polished wafers at 50% fracture probability is 217

*Instron Corporation, Model 1122, Canton, MA.

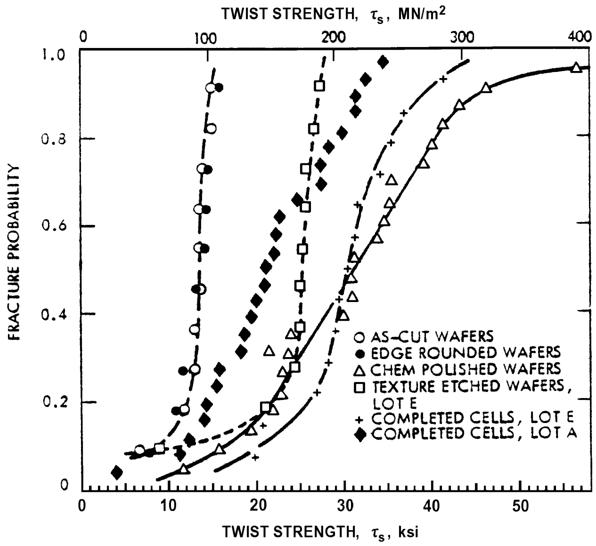


Figure 6. Effect of Manufacturing Processes on the Twist Strength of Silicon Wafers and Cells

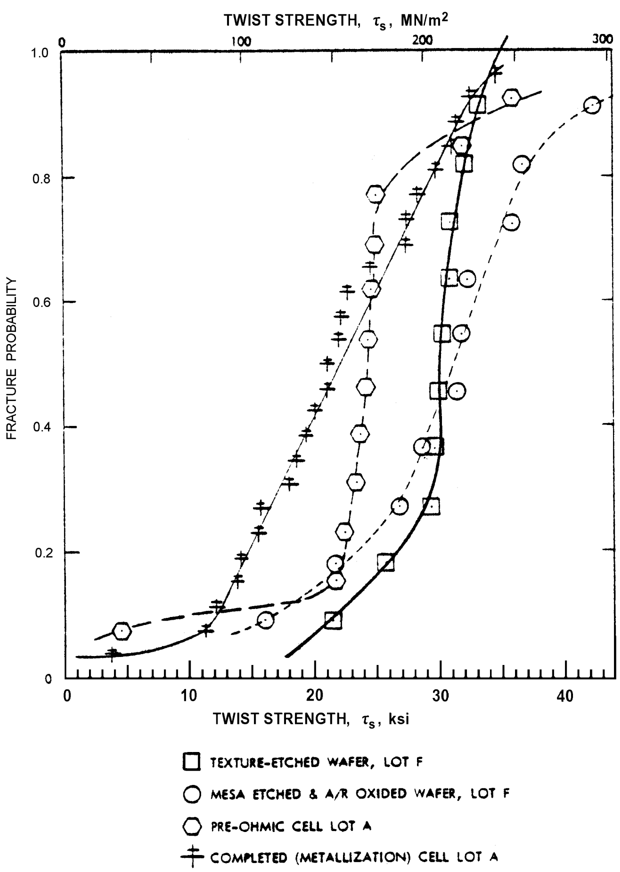


Figure 7. Effect of Metallization and Other Processes on the Strength of Solar Cells

MN/m^2, which is more than twice the strength of as-cut wafers. A reduction of flaw size must occur during the chemical etching process, since the strength of wafers is determined by the critical flaw size. Chemical polishing appears to be more effective in reducing smaller flaws than larger flaws; the slope of the Weibull plot for the strength of chemically polished wafers is smaller than that for as-cut wafers. This implies that more etching on the wafer edge may be necessary to reduce further the larger flaws and to improve the strength of silicon wafers.

3. The twist strength of texture-etched wafers, lot E, at 50% fracture probability is 176 MN/m^2, which is higher than that of as-cut wafers. This suggests that etching is effective in improving the strength of wafers. Texture etching reduces the surface damage from ingot cutting and replaces it with uniform pyramidal etch pits. Therefore, the slope of the Weibull plot for texture-etched wafers is greater than that of chemically polished wafers. It is important to note that a tail below 20% fracture probability on the strength distribution curve is usually found in each wafer category. As seen in Figure 6, an appreciably long tail in the minimum-strength end of the curve is found in this lot of texture-etched wafers. Texture-etched wafers below the 20% fracture-probability curve were particularly vulnerable to fracture during subsequent cell processing and handling.

4. The twist strength of completed cells (lot E) at 50% fracture probability is 214 MN/m^2. These cells were fabricated from the same lot as were the texture-etched wafers. The strength of completed cells appears to be increased by metallization (Figure 6).

5. The comparison of the strength of mesa-etched and antireflection (AR) coated wafers with that of texture-etched wafers of the same lot (lot F) is shown in Figure 7. Mesa etching and AR coating tends to increase strength slightly at the higher stress levels, suggesting that mesa etching and AR coating processes reduce small surface flaws more effectively than they do large flaws.

6. A comparison of the strength of pre-ohmic cells and that of completed cells of the same lot (lot A) is shown in Figure 7. Completed cells were processed from pre-ohmic patterned cells by metallization with a thickness of approximately 100 m. The strength of completed metallized cells should be greater than that of pre-ohmic cells, but as seen in Figure 7, the strength of completed (metallized) cells was found to be lower than that of pre-ohmic cells at most stress levels of the strength distribution curves, the opposite of the expectation. Preliminary examination indicated that edge chips and surface flaws are related to the weakening of the completed cells from lot A. These chips and flaws were apparently extended or generated by the metallization of lot A. It should be pointed out that strength distribution curves of pre-ohmic and completed cells have long tails

extending to the low stress levels. Since it appears that the large critical flaws obtained in a cell process step are carried on to subsequent processes, extension of these flaws under stress is expected. Proof testing, useful for eliminating weaker wafers and cells and thus truncating the strength distribution curves of ceramics (9), should be used at early stages of processing.

7. The typical fracture mode of tested wafer specimens is shown in Figure 8. Specimens that fractured into smaller fragments were found to have greater strength than those that fractured into fewer, larger fragments; more energy was available to fracture a larger number of small flaws simultaneously. Microscopic examination indicated that fractures of cell samples are initiated at critical edge flaws.

CONCLUSIONS

1. Chemical polishing is useful for reducing the surface flaws of silicon wafers. A greater-than-twofold increase in mean strength of wafers results from chemical polishing. It is more effective in the reduction of the smaller flaws than of larger flaws. A greater increase in strength is found at higher strengths than at the lower-strength portion of the distribution curve.

2. Texture etching reduces the surface damage resulting from ingot cutting, so that the overall strength of a textured wafer is higher than that of an as-cut wafer. Chemical polishing appears to be more effective than texture etching in reducing surface flaws.

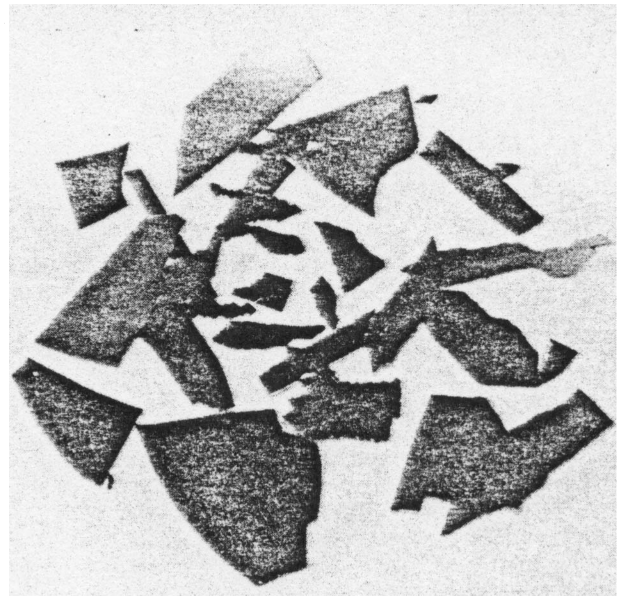
3. Mechanical edge rounding does not produce significant change in the strength of the silicon wafer.

4. Mesa etching and AR coating of wafers and pre-ohmic (patterned) cells result in little change in strength from the preceding process.

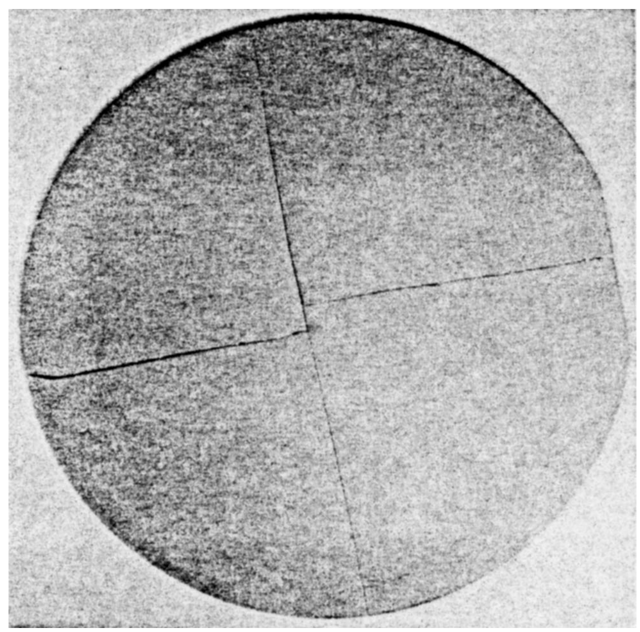
5. Edge flaws that were generated during processing and handling of samples were found to be a major factor in the measured strength of samples.

6. A long tail at the low-stress portion of the strength distribution curve was found for several types of samples. The wafers or cells in the low-strength distribution are likely to be fractured during subsequent cell processing and handling or in field service. A proof test would be useful to eliminate these samples.

7. The Weibull distribution plot of strength data is useful to describe the strength characteristics of wafers or cells at various process steps and to describe the flaw distribution of each sample.



Small Fragments



Large Fragments

Figure 8. Typical Fractures of Silicon Wafers Subjected to Four-point Twisting

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