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Effect of reciprocating wire slurry sawing on surface quality and mechanical strength of as-cut solar silicon wafers

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ABSTRACT

This paper investigates reciprocating wire slurry sawing for photovoltaic (PV) silicon wafering and compares the resulting wafer surface quality and its mechanical strength to that obtained in unidirectional wire sawing. It is found that wire reciprocation creates two significantly different morphological or cutting zones on the wafer surface. The zone width varies with the distance travelled by the wires, the cutting location on the wafer surface, and direction of wire motion. The size of the morphological zone created during forward motion of the wire is larger than that created during its backward motion. The zone width is found to decrease along the wire cut direction. In addition, there appears to be greater kerf loss and increased surface roughness in the forward cutting zone. In general, results suggest a higher material removal rate during forward motion of the wire than during backward motion. Notwithstanding the surface morphology variations, the fracture strengths of reciprocating wire sawn wafers are found to be quite similar to that exhibited by wafers produced by unidirectional wire sawing.

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1. Introduction

Crystalline silicon wafer based photovoltaic (PV) solar cells account for more than 85% of the market share today [1]. There is great interest in reducing the materials and manufacturing costs of solar cell technologies in order to increase their economic viability. This interest has led to the advent of a variety of new technologies in PV manufacturing, such as, mono-like silicon casting [2,3], diamond wire sawing for silicon wafering [4,5], direct or double printing for electrical interconnects [6,7], in addition to many new cell structures [8,9].

In the area of wafer production, there continues to be a need for lowering the wafering cost [10]. Basically, there are two possible approaches that can be used to lower wafer cost: (i) use thinner wafers, and (ii) increase sawing throughput while lowering the usage of consumables such as slurry and wire. The first approach faces a technological challenge in wafer handling, since thin wafers (~180 μm) are extremely fragile and break easily during handling and/or transport [11]. On the other hand, the second alternative consists of improving and optimizing the wafering process.

The most commonly used silicon wafering technique is multi-wire slurry sawing, which replaces traditional ID sawing [12]. Silicon bricks are fed through a web of parallel wires, thereby slicing a thousand or more wafers simultaneously. Wire sawing machines typically permit either unidirectional or reciprocating wire motion. In either method, the actual cutting process is undertaken by the hard silicon carbide abrasives entrained in the cutting channels by the fast moving wires [13].

As the wires used in silicon wafering are 10s of kilometers long, wire consumption can be reduced by using reciprocating wires. In this paper, we analyze the effects of reciprocating wire sawing on the surface quality and fracture strength of as-cut silicon wafers. The corresponding sawing mechanisms are also discussed.

2. Experimental

Multicrystalline 156 mm × 156 mm silicon wafers of 200 μm nominal thickness were cut under various sawing conditions by an industrial multi-wire slurry saw located at a vendor facility. The reciprocating wire sawing process employed used two cutting schemes – a short cycle and a long cycle scheme. Table 1 lists the wire travel distances and other sawing parameters used. In the short cycle scheme, the overall travel distances for both the forward and backward motions are small but have a larger backward/forward (B/F) ratio. In the long cycle scheme, the travel distances for both the forward and backward motions are greater but with a smaller B/F ratio. A third case with unidirectional wire motion is included for benchmarking purposes. The table speed, wire speed, and acceleration of the sawing process are the same for the three sawing conditions.

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Table 1
Details of reciprocating and unidirectional wire sawing conditions.

Cut scheme	Table speed (μm/min)	Wire speed (m/s)	Acceleration (m/s^2)	Forward distance (m)	Backward distance (m)	B/F ratio
Short cycle	500	22	5	500	375	0.75
Long cycle	500	22	5	1000	520	0.52
Uni-directional	500	22	5	–	–	–

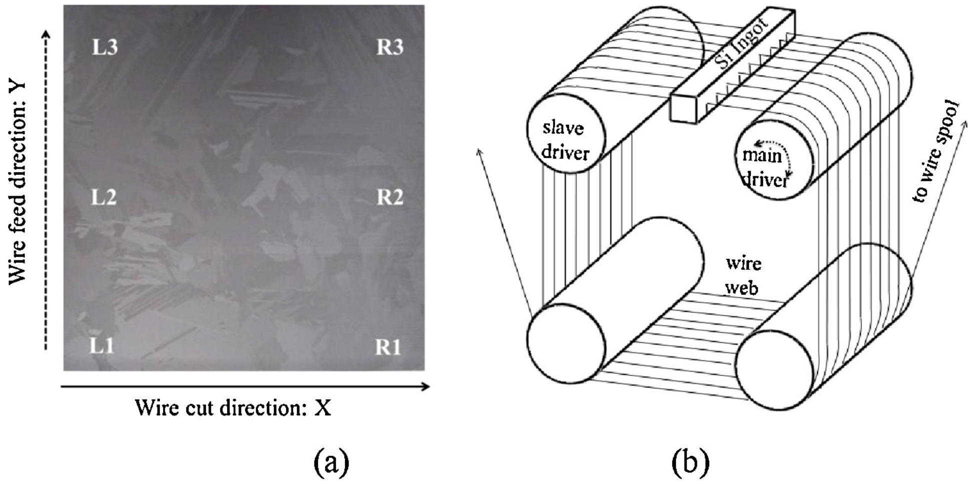

Fig. 1. (a) Photograph of a representative wafer showing the measurement locations on the left and right side of a wafer at three feed positions (from 1 to 3 which corresponds to the beginning and ending of the feed direction), (b) a schematic of a multi-wire slurry saw.

The as-cut wafers are characterized by several metrics, including surface roughness, wafer thickness variation, fracture strength, and cutting zone width. As there are two distinct cutting/morphological zones on wafers produced by the reciprocating wire, the cutting zone widths generated by the forward and backward motions were measured separately using optical microscopy performed at different locations on the wafer surface. Fig. 1a shows the measurement locations on two edges (left and right) of a wafer, as well as the wire forward motion (*X*) and feed direction (*Y*). For reference, a schematic of a multi-wire slurry sawing system is shown in Fig. 1b. The sawing process is conducted by a high speed moving wire in the environment of a grit-containing slurry manifold at wire entry. The cutting wire moves in one direction for unidirectional wire sawing, but moves back and forth in reciprocating wire sawing. The markers on a wafer represent approximately the wire entry and exit points at three different ingot/wafer depths (from 1 to 3). The surface roughness in each zone was measured by a 3D laser confocal microscope. Surface morphology was analyzed by a scanning electron microscope (SEM). The wafer thickness variations in the wire velocity and feed directions were measured along the centerlines of two orthogonal directions on wafers.

The fracture strength of the as-cut wafers was measured using a four line bending method, which has a 60 mm loading distance and 120 mm supporting span. Due to the large elastic deflection (in the range of 4–7 mm) of the wafers during bending, the wafer fracture strength was calculated by the finite element method (FEM) using non-linear large strain elasticity theory.

3. Results and discussion

3.1. Cutting zone width

The most distinguishing feature of the reciprocating wire sawn wafer surface is the repetitive pattern of two alternating cutting zones produced by the back-and-forth wire motion. Fig. 2 shows a comparison of reciprocating wire and unidirectional wire sawn wafer surfaces. Parallel cutting zones are clearly visible, indicating a different surface morphology created by the forward and backward cutting processes (Fig. 2a and b). The cutting zone width varies with the total wire travel distance. It can be seen that the forward zone width due to the forward wire motion is larger than the backward zone from the backward motion. The cutting zone width varies with the wire cycle scheme as well due to the travel distance. In comparison, the unidirectional wire sawn wafer surface is uniform and homogeneous (Fig. 2c).

The cutting zone widths at the six different locations as shown in Fig. 1 were measured. Table 2 shows a comparison of the measured cutting zone widths. It is clear that the cutting zone width varies greatly on a wafer, even though they are all cut with the same forward and backward wire travel distances for a given cycle scheme. Albeit complicated, a careful examination yields the following conclusions regarding the variation of cutting zone width in a wafer. First, the cutting zone width is always greater in the forward direction than in the backward direction due to the longer wire travel distance associated with the forward direction. This is also reflected in the B/F cutting width ratio, which is always less than unity. Second, the cutting zone width near the wire entry region is almost always greater than that near the wire exit for both cycle schemes. This trend can be better seen in Fig. 3, where the solid red lines representing wire entry location are mostly above the blue dotted lines that represent the corresponding wire exit, except in one case. The cutting zone width also varies in the feed direction, especially in the forward motion direction. That is, there is a gradually decreasing cutting zone width from the bottom to the top of a wafer (Fig. 3a). However, this trend is not as clear in the backward motion direction (Fig. 3b).

It can be also seen from Table 2 that the B/F cutting width ratio differs with location. There is usually a smaller B/F ratio in locations near left edge, which corresponds to the wire entry region in the forward motion case but corresponds to the wire exit region in the backward motion case. The average B/F ratio is 0.53 for the short cycle and 0.41 for the long cycle on the left side of the wafer, and 0.61 for the short cycle and 0.54 for the long cycle on the right side of the wafer. Except in one case, these cutting width ratios