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Technical Note

Crack detection in single-crystalline silicon wafers using impact testing

C. Hilmersson, D.P. Hess *, W. Dallas, S. Ostapenko

University of South Florida, Tampa, FL 33620, USA

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Abstract

This paper presents acoustic measurements obtained by mechanically exciting vibratory modes in single-crystalline silicon wafers with hairline periphery cracks of different type and location. The data presented shows a dependence of natural frequencies, peak amplitudes and damping levels of four audio vibration modes in the frequency range up to 1000 Hz on crack type and crack location. Data from defective wafers exhibit lower natural frequencies, higher damping levels, and lower peak amplitudes. The results suggest an impact test method may be useful for solar cell crack detection and quality control.

Keywords: Silicon wafer; Solar cell; Crack; Detection; Audible; Vibration

1. Introduction

Crystalline silicon is the most common material used in the photovoltaic market with over 85% of the market share. The primary reason the photovoltaic cell is not more widespread is cost, particularly the cost of cell production. During crystal growth and processing of silicon wafers, mechanical imperfections (such as cracks, residual stresses [1] and sub-surface damage) are introduced. Breakage during production due to defects is currently 6–15%, but the industry is striving to get this down to 1%. In-line wafer breakage also reduces equipment throughput as a result of downtime and the need to stop and cleanout machinery to remove broken wafers from fixtures which is typically a manual process. Hence, there is a need for fast, non-destructive, in-line mechanical quality control methods to detect these imperfections during production. Such methods could reduce further processing of defective product and reduce overall costs.

Cracks in single-crystal Czochralski Silicon (Cz–Si) solar cells are generally introduced on a cleavage plane and are not visible with the human eye. The critical length of such cracks is about 1 cm. At this length and higher, they propagate in production from handling and further processing.

Existing methods used to detect cracks include scanning acoustic microscopy (SAM) [1], optical transmission [2], ultrasound lock-in thermography [3], luminescence [4,5], and resonance ultrasound vibration [6].

The SAM [1] method of crack assessment is not feasible for mass production of photovoltaic cells because the time required to scan a 100 mm by 100 mm wafer is between 10 and 15 min. Additionally, the wafer has to be submerged in a water bath or covered with a water droplet. However, this approach does allow for cracks as small as 5–10 μm to be detected.

The optical crack detection system utilizes the transmission of a high intensity flashlight through the wafer and captures the image with a CCD camera coupled with optical filters [2]. Processed wafers with the Al backside coating and final solar cells practically inhibit this form of crack detection. Additionally, the cracks in Cz–Si wafers can be closed having the width below the optical diffraction limit of approximately 1 μm. This makes them invisible in the transmission test.

Ultrasound lock-in thermography can be used to detect cracks with lengths as small as 100 μm, but also requires

* Corresponding author. Tel.: +1 813 974 5643; fax: +1 813 974 1447.
E-mail address: hess@eng.usf.edu (D.P. Hess).

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too much processing time to be feasible for mass production use [3].

The luminescence imaging employs the fact that under laser excitation or using forward bias, the Si wafer or solar cell emits infrared light due to band-to-band electron-hole recombination [4,5]. These methods rely on cooled CCD cameras to detect the near-infrared part of the emission. Cracks or defects are expected to reduce minority carrier lifetime, therefore reducing luminescence efficiency. Though luminescence methods are fast and non-destructive, other types of defects such as surface scratches and dislocations may interfere and misinterpret the crack identification.

Recently reported resonance ultrasound vibrations methodology is fast, matching the few seconds per wafer throughput rate of modern solar cell production lines and capable of non-destructively detecting sub-centimeter length periphery cracks [6].

The basis of the method presented in this paper is that the audible impact response from a cracked component sounds different than that of a non-cracked component. A simple demonstration can be made by comparing the response from tapping an undamaged glass with a cracked glass. The difference is readily detected with the human ear. A similar demonstration can be performed with silicon wafers, and in fact a notable difference is detected with the human ear. This paper presents data from an investigation aimed at more formally assessing this difference using an impact test method. A similar approach was recently demonstrated to assess residual elastic stress in multi-crystalline Si wafers [7].

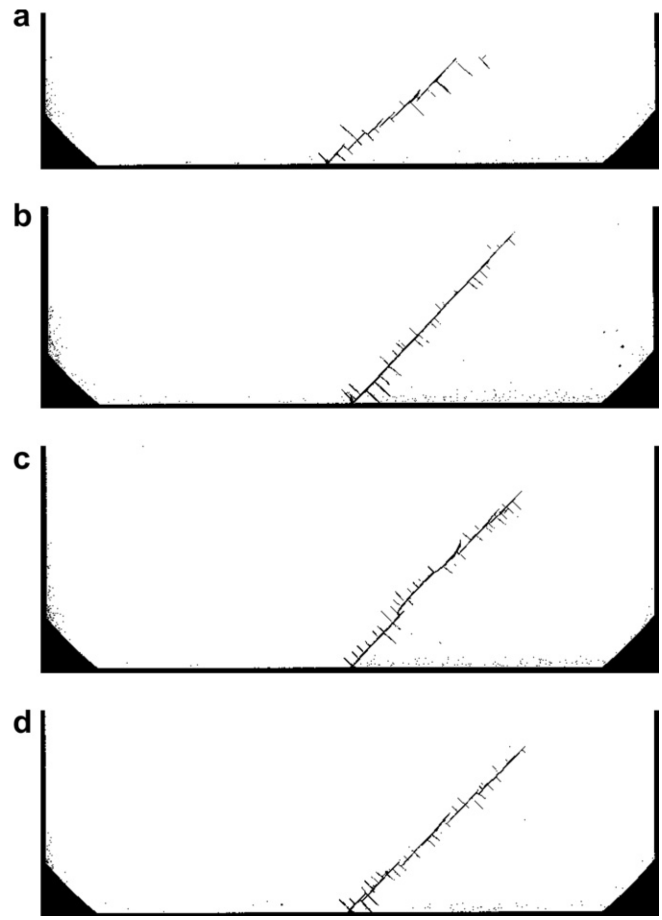

Fig. 1. Center crack wafers: (a) 39, (b) 31, (c) 35 and (d) 48.

2. Test specimens

A set of 125 mm × 125 mm single-crystalline pseudo-square shaped (1 0 0) oriented Czochralski (Cz) silicon wafers was used in this study. Four of the wafers are crack-free and twelve of the wafers have cracks. The cracks are introduced in the wafers by pressing a diamond pin on the edge of the wafers with a light force equivalent to the force used in writing. With this approach, the human ear can hear the wafer crack. To quantify crack length and position, all wafers are scanned by scanning acoustic microscopy (SAM) before and after the impact testing.

The crack lengths obtained with this approach range from 38 mm to 55 mm. Some of the cracks begin at the center of an edge of a wafer, while others are offset. Some have continuous cracks and some have segmented cracks, i.e., a series of small cracks in sequence. High resolution SAM images reveal evenly segmented cracks in wafers numbered 39, 32, 36, 40, 8, 6 and 41. Wafers numbered 48 and 33 are segmented but the initial crack from the edge is significantly longer than the remaining sequence. Wafer number 27 initially had a segmented crack but during the impact testing it became continuous. Finally, wafers numbered 31 and 35 have continuous cracks.

The cracks are also classified according to edge location. Wafers numbered 39, 31, 35 and 48 have cracks initiating on the center of an edge and are shown in Fig. 1. Wafers numbered 32, 40, 36, 27, 8, 6, 33 and 41 have cracks initiating offset from the center of an edge and are shown in Fig. 2. Table 1 lists the characteristics of the sixteen test wafers used in this work.

3. Impact tests

The test setup is shown in Fig. 3. The test wafer is centered on convoluted foam. Impacts are applied to the wafer using a miniature piezoelectric impact hammer with a vinyl tip, weight of 2.9 g and length of 10 cm. The impact response is measured with a microphone mounted 2 cm above the test wafer. The position of the hammer and microphone tips with respect to the wafer is shown in Fig. 4. These positions were found to provide adequate response levels for the first four audible modes of wafer vibration.

A dynamic signal analyzer is used to record the impact hammer force input, F, (in units of Newtons) and the resulting sound pressure level response, S, (in units of dB). The analyzer calculates the frequency response with the impact force defined as the input and the sound pres-