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Residual stresses in multi-crystalline silicon photovoltaic wafers due to casting and wire sawing

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ABSTRACT

A significant portion of the total manufacturing cost of crystalline silicon solar cells is attributed to the manufacturing and material costs of the silicon wafer. In addition to its high cost, silicon is very brittle, therefore wafers are prone to fracture during handling and processing. In this paper we investigate the manufacturing-induced residual stresses in photovoltaic silicon wafers due to casting and wire-sawing processes which affect the mechanical integrity of the wafers. Specifically, the paper addresses measurement of residual stresses in multi-crystalline silicon (mc-Si) wafers by photoelasticity and polarized micro-Raman spectroscopy methods, as well as the effects of diamond wire sawing and loose abrasive slurry sawing on the residual stresses within the grains and at the grain boundaries. The micro-Raman method probes the residual stresses in the near-surface of the wafer while the photoelasticity technique probes the through-thickness residual stress in the wafers. The results show that diamond wire sawing and loose abrasive slurry wire sawing produce compressive residual stresses in the as-cut mc-Si wafer surface. Loose abrasive slurry wire sawing produces larger compressive stresses in the as-cut surface layers compared to diamond wire sawing. Beneath the saw damage layer in the sawn wafers, low residual tensile stresses are present from the casting process.

1. Introduction

1.1. Background

Understanding manufacturing-induced residual stress in multi-crystalline silicon (mc-Si) wafers is critical for improving the wafer mechanical integrity in order to increase production yields and to reduce the total cost of photovoltaic (PV) solar cell manufacture. The material and manufacturing costs of silicon wafers comprise approximately one-quarter of the overall cost of solar cell production [1]. In addition to the prohibitive cost of manufacture, silicon is a brittle material, and wafers are made increasingly thin (180 µm or less) to optimize material use.

During solidification of a cast mc-Si ingot, a thermal gradient is created by the temperature distribution, which results from non-uniform cooling and a non-planar solid-liquid front [2]. The thermal gradient produces residual stresses in the ingot [3,4]. In addition, wire sawing processes such as loose abrasive wire sawing (LAWS) or diamond wire sawing (DWS) used to slice the ingot into individual wafers produce residual stress and damage (micro-cracks, pits, spalling) in the near-surface of the wafers due to mechanical interaction of the abrasive grits and silicon. Residual stresses in PV mc-Si wafers generated by ingot casting and subsequent wire sawing-based wafer production processes contribute to early fracture and breakage of the wafers during wafer processing and handling, which increases the production cost solar cells.

To date, the direct contributions of residual stress in mc-Si wafers due to the thermal gradients produced in casting and due to wire sawing processes have not been analyzed in detail. This paper aims to experimentally quantify and analyze the residual stress magnitudes, type (tensile, compressive), and the spatial residual stress distributions in the wafer due to casting and due to wire sawing processes, namely, LAWS and DWS. By analyzing the contributions of these two manufacturing processes to the residual stress in mc-Si wafers, the understanding of wafer mechanical integrity can be improved. It should be noted that previous studies of fracture and breakage of PV silicon wafers utilize wafer bending tests and rely on statistics to quantify wafer mechanical integrity [5–8]. While these studies are useful, they are unable to isolate the contributions of the different manufacturing processes to the residual stress.

Several studies have been conducted to understand residual stress in mc-Si wafers. Popovich et al. [9] and Echizenya et al. [5] used micro-Raman spectroscopy to measure the residual stress in the saw damage layer of mc-Si LAWS wafers. The residual stress in the saw damage layer

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was reported to be compressive, and equal to 500 MPa using a biaxial stress assumption [9]. Echizenya et al. [5] reported the stress as a function of the etch depth and found a decrease in compressive stress through the depth of the wafer as a function of the distance from the as-sawn wafer surface. Additionally, Würzner et al. [10] performed scribing on mono-Si using single diamond particle tips to investigate the cutting mechanism in DWS. Raman spectroscopy peak shift measurements revealed the stress state created by DWS scribe tests to also be compressive, however the stress magnitudes were not reported. Yang et al. [11] used the same near-infrared birefringence polariscope used for in experiments described in this paper to investigate the residual stress in DWS mc-Si wafers before and after wet chemical etching using HF/HNO3, which removed 5 µm of the DWS wafer surface. The results showed that after etching, both the maximum and average maximum residual shear stress, τ_{max}, in the wafers decreased and the fracture strength improved. Based on reports of micro-crack lengths [8,12,13], it has been determined that micro-cracks in DWS wafers can extend to lengths greater than 5 µm, and therefore the saw damage layer was not completely removed in this experiment. Consequently, the results did not ascertain the effect of DWS on residual stress.

In addition to these studies of wire sawing induced residual stress, experimental studies have been conducted to compare the residual stress in the center of grains versus at grain boundaries in mc-Si wafers [14–17]. Differences in the stresses at the center of the grains and at grain boundaries were reported in the range of tens of MPa [18]. Popovich et al. [9] used micro-Raman spectroscopy to measure the stress at the center of grains and at grain boundaries under an applied tensile load. Residual stresses at the grain boundaries were found to be 50–70 MPa higher than the residual stress within the grain under tensile load. Popovich et al. concluded from this finding that the grain boundaries are the most likely source of reduction in the strength of mc-Si wafers.

Recently, Pogue et al. [19] measured residual stress using micro-Raman spectroscopy in cast mc-Si wafers with the saw damage layer fully removed by wet chemical etching and reported tensile stresses in the regions studied. Additionally, Jagailloux et al. [20] used a near infrared birefringent polariscope to compare stresses produced by LAWS, DWS, and casting. While the authors compared the magnitudes of stress for the processes, the stress type (tensile versus compressive) was not analyzed.

1.2. Approach

Near-infrared birefringence polariscopy and polarized micro-Raman spectroscopy, respectively, are used in this paper to measure and analyze the through-thickness and surface residual stresses, respectively, in mc-Si wafers. While near-infrared birefringence polariscopy provides a full-field through-thickness residual stress measurement based on the principles of photoelasticity, polarized micro-Raman spectroscopy uses the Raman effect to measure the localized near-surface residual stress. In addition, wet chemical isotropic etching is used to understand the variation in residual stress as a function of mc-Si wafer depth, both at the wafer surface where saw damage is present, and in the bulk of the wafer, where residual stresses are primarily generated by the casting process.

2. Experimental method

2.1. Design of experiments

Two experiments were designed to address the research objectives. “Experiment A”, was designed to delineate the contributions of residual stress caused by saw damage and by the thermal gradient produced in mc-Si ingot casting. "Experiment B" was designed to provide a better understanding of the saw damage layer by studying the residual stresses in the first 12 µm of the silicon wafer. Table 1 summarizes the two experiments.

2.2. Experiment A

Experiment A was designed to delineate the residual stress produced by saw damage from the residual stress produced by the ingot casting process. A process flow diagram demonstrating the experimental approach used is shown in Fig. 1.

Single mc-Si DWS and LAWS wafers were used in this experiment. Each wafer (one DWS and one LAWS) was etched progressively to the following etch depths using a wet chemical isotropic etchant, HNA ($HF:HNO_3:CH_3COOH$) (9:75:17) [21,22]: 0, 0.5, 8, 16, 25, and 40 µm. Both sides of the wafers were etched to the same depth in each case, i.e. for the 12 µm etch depth case, 12 µm was removed from each side of the mc-Si wafer. For consistency, in this paper, the term “etch depth” always refers to the depth removed from one side the wafer. At each etch depth, the residual stress in each wafer was characterized in specific regions of interest using polarized micro-Raman spectroscopy.

2.3. Experiment B

Experiment B was designed to measure and analyze the residual stress in the first 12 µm of the saw damage layer. A process flow diagram of the experimental approach is shown in Fig. 2.

Multi-crystalline silicon “sister wafers” of each sawing process type, DWS and LAWS, were first diced into quadrants to facilitate handling and to allow for replication of experiments, if needed. Sister wafers are adjacent wafers taken from the same brick of the same ingot and are therefore assumed to possess similar wire-sawing induced residual stress and similar thermal gradient induced residual stress resulting from the mc-Si ingot casting process.

Seven sister DWS mc-Si wafers and seven sister LAWS mc-Si wafers were etched using a wet chemical isotropic etchant, HNA ($HF:HNO_3:CH_3COOH$) (9:75:17) [21,22] to obtain the residual stresses at each of the following etch depths: 0, 2, 4, 6, 8, 10, and 12 µm. The thickness of the wafer was calculated before and after etching using the formula,

$$t = \frac{m}{\rho l w} \tag{1}$$

where t is the thickness of the wafer, m is the measured weight of the wafer in grams, ρ is the density of Si, 2.33 g/cm^3 [23], and l and w are the length and width of the wafer, respectively.

2.4. Polarized micro-Raman spectroscopy

In typical Raman spectroscopy based measurement of stress in single crystal silicon, the crystallographic orientation of the sample is known prior to the measurement. In the case of mc-Si, the crystallographic orientations of the grains present in the wafer are not known, as they are random and dependent on crystal growth during the casting process. The polarized micro-Raman spectroscopy method used in this paper to measure the local residual stress state of mc-Si was developed by Becker et al. [16]. Using their method, each crystal in the mc-Si sample is treated as a single crystal to determine its orientation. Becker et al. utilized the well-established dependence of polarization on the scattering efficiency (see Eq. (2)) to determine the crystallographic orientation of grains of unknown orientation in mc-Si wafers.

$$I(\overrightarrow{e_i}, \overrightarrow{e_s}) \approx I_0 \cdot \sum_{j=1}^{3} |\overrightarrow{e_i} \cdot R'_j \cdot \overrightarrow{e_s}|^2 \tag{2}$$

Eq. (3) incorporates an adjustment to Eq. (2), which includes a transformation matrix, $\mathbf{T}(\alpha, \beta, \gamma)$, to allow for rotation between the laboratory and crystal coordinate systems.