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Stiffness and fracture analysis of photovoltaic grade silicon plates

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A B S T R A C T

The rigidity and the strength of photovoltaic cells, particularly the centerpiece-embedded silicon plates, are of great importance from an economical point of view since their reliability impacts the overall cost based on production, transportation and in-service use. The present work focuses on the solar-grade multi-crystalline silicon used in PV wafers. The aim is to characterize the Young's modulus and to analyze the fracture behavior at room temperature. The Si plates have been laser cut from two different manufacturing processes of silicon wafers, MCSi and RST. Due to the brittle behavior of Si at ambient temperature, 4-point bending tests have been performed. The beam hypothesis has been used to analyze bending tests for determining the Young's modulus. A correction strategy has then been proposed with a numerical model in order to determine with a higher accuracy the mechanical data and the measurement uncertainty. For fracture investigation, high speed imaging technique and fractography have been used to identify the failure mode as well as the crack origin. The Young's modulus is found to be 166 ± 5 GPa for MCSi wafers. The anisotropic stiffness of RST plates is also revealed and correlates well with the micro-structural texture. Both kinds of plates fracture in trans-granular manner from the edges, where some defects are located due to laser cutting.

1. Introduction

In the photovoltaic (PV) domain most of the literature deals with the improvement of the electrical efficiency, by acting on some physico-chemical parameters. However, it is also important to address the material stiffness and the fracture behavior of the silicon wafers, since (i) many silicon wafers break during the manufacturing process before the integration in PV cells and (ii) post-manufacturing cracks created during transportation, installation or production can significantly decrease the efficiency of PV modules (Köntges et al., 2011; Paggi et al., 2014). Knowing that the fabrication cost of silicon wafers represents up to 40% of the total cost of a PV module (Möller et al., 2005), advanced manufacturing processes for thinner or more robust silicon wafers emerge increasingly. The characterization of the mechanical properties are of great practical interest, as the material's rigidity and fracture strength are highly influenced by the crystallinity and fabrication process (Popovich et al., 2011).

Crystalline silicon used in solar modules is of high purity. The silicon is a material whose mechanical properties depend on the temperature (Bourgeois et al., 1997; Masolin et al., 2012). It is, whether in the forms of single crystal or multi-crystal, a very brittle material at ambient temperature and it presents a brittle-ductile transition at temperature of about 600 °C (Brede, 1993; Hull, 1999). Above this transition temperature, Si can undergo large plastic deformation due to dislocation movements, as discussed by Alexander and Haasen (1969).

Many investigations were carried out to characterize the stiffness of mono-crystalline silicon. Due to the cubic symmetry of the atom arrangements in the crystal lattice, the material owns only three independent parameters in the elastic stiffness tensor (Hopcroft et al., 2010; Hull, 1999; Masolin et al., 2012). The most accepted values were given by Hall (1967) from sound-velocity measurements. For multi-crystalline silicon, the rigidity depends on the distribution of crystallographic orientations of the grains. Indeed, a multi-crystalline silicon can be considered as an aggregate of multiple single grains separated by grain boundaries. If the average grain size is negligible compared to the dimensions of the studied structure, the multi-crystal can be homogenized into an isotropic material with only two parameters, the Young's modulus and the Poisson's ratio. The appropriate values of poly-crystalline silicon used for MEMS systems were reported by Sharpe Jr (2001) (E = 160 GPa; ν=0.2). Funke et al. (2004) performed an analytical calculation over a representative volume element and gave E = 162.5 GPa; ν=0.223 which were used for PV grade multi-crystalline silicon. However, these results should be used with caution for our application because the typical grain size is in

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centimeter range, which has almost the same order of magnitude as the specimen's dimension. Furthermore, if a specific texture exists, the characterization should account for the loading direction (bending axis here).

The silicon is brittle at room temperature. In the literature, most of the attention was paid to the fracture of single crystal. It is widely accepted that the cracks take place on the {1 1 1} and {1 1 0} crystallographic planes (Ebrahimi and Kalwani, 1999; Hauch et al., 1999; Holland and Marder, 1998; Pérez and Gumbsch, 2000; Sherman, 2009). Ebrahimi and Kalwani (1999) investigated the fracture toughness and the fracture path within a single crystalline silicon with Vickers micro-hardness indentation. Hauch et al. (1999) and Li et al. (2005) reported the critical fracture energy of artificial pre-cracked silicon thick plates with an uni-axial tension apparatus. Many experimental investigations were based on 3 or 4-point bending tests (Sherman, 2003; 2009; Sherman and Be'ery, 2003), with the use of fractography to study the morphology of the crack surface. Regarding the multi-crystalline silicon, Brodie and Bahr (2003) investigated the influence of grain size on the fracture toughness. The results indicated that the latter has little dependence on the grain size when the typical size is over 30 µm.

Whereas the improvement of the energetic efficiency of PV cells has captured since many years most of the efforts from the scientific community, mainly chemists and physicists, little is known about the thermo-mechanical strength and the fracture behavior of crystalline silicon plates, in itself or when embedded in a ready-for-use PV cell, under static or dynamic loading. In solar cell scale, Sander et al. (2013) investigated the crack pattern in encapsulated solar cells based on 4-point bending tests. Bending tests on flexible PV modules with initial cracks in silicon cells have also been performed in Paggi et al. (2014). In that case, the role of fracture on the electric response was for the very first time monitored using the electroluminescence technique during the deformation process (for both monotonic and cyclic loading). Kaule et al. (2014) studied the mechanical strength with different loading configurations relative to busbars. Kohler et al. (2014) performed photo- and electroluminescence analyses to locate defects such as material inhomogeneities or cracks. At the wafer scale, the former works concentrated mostly on the fracture stress with Weibull distribution in order to analyze the influencing factors. Funke et al. (2004) carried out biaxial tests to investigate the behavior of different kinds of wafers. Popovich et al. (2011) highlighted the effect of the crystallinity with 4-point bending tests. However, the fracture origin studies for multi-crystalline silicon wafer are rare to see. An interesting work was performed by Klute et al. (2014) who investigated the fracture origin for as-cut monocrystalline silicon wafers using fractography.

In this study, we are focusing on the mechanical strength of Si plates which stem from two different silicon wafer fabrication processes, i.e. classical sawing of multi-crystalline silicon produced by the ingot cast process (called MCSi) and Ribbon on Sacrificial Template process (called RST) (De Moro et al., 2012). The objective is to characterize the stiffness and to analyze the fracture behavior of these two kinds of plates at room temperature. 4-point bending tests were used for the overall study. Concerning the rigidity, we applied the beam theory to calculate the Young's modulus. A Finite Element (FE) model was carried out in order to analyze experimental data – with a correction procedure – and assess the overall rigidity with numerical simulations. Regarding the fracture behavior, high speed imaging technique and fractography were used to explore the fracture modes and sources.

The first part of the paper presents in details our samples, their fabrication and the induced micro-structures. A second part is dedicated to the experimental set up and presents the methods for the rigidity characterization and the fracture investigations. In the third part, the FE model is presented along with a correction strategy to better assess the Young's modulus from bending experiments. The fourth part presents the main results, followed by a discussion on the results and then the conclusion.

2. Presentation of the studied PV grade silicon

2.1. Description of the specimens

As mentioned in the introduction, the specimens come from two kinds of manufacturing processes, MCSi and RST (detailled in Section 2.1.1 and 2.1.2). Both kinds of plates are laser cut from silicon wafers to obtain the square shape of size 50×50 mm^2. The RST plates are thinner (90 µm thick) than the MCSi plates (170 µm thick).

The following paragraphs detail the two different manufacturing processes and the induced micro-structures.

2.1.1. MCSi ingot cast

The MCSi manufacturing process is based on the solidification of melt silicon into ingot cast. As presented in Fig. 1, the crystal growth is controlled in a heated furnace where inert gas (argon) is injected in the crucible to guarantee an oxygen-free environment. After solidification, the ingot can be removed out of the furnace through the bottom opening. The ingot is then sawed into circular slices over the desired thickness. Wire sawing ensures good flatness and low roughness to the wafer. The latter is finally laser cut to get the final plate shape and size.

The characteristic grain shapes are presented in Fig. 2. Most grains are of a centimeter wide, that should be compared to the plate thickness (170 µm for MCSi specimens). The grain boundaries are quite visible to the naked eye. It reveals that the grain shape is mostly polygonal with an aleatory distribution. In addition thin strips of twinning can be distinguished by light reflection contrast in many grains. They are parallel to each other in one grain but their orientation differs from one grain to another, which is a characteristic feature of grain disorientation.

2.1.2. RST crystal growth

RST manufacturing process aims to produce thinner silicon wafers in order to reduce the global cost of PV modules. As shown in Fig. 3, this kind of wafers is obtained by drawing a graphite ribbon through a crucible of molten silicon. The latter solidifies continuously on the two sides of the ribbon when it comes out of the crucible. A thin layer of pyrocarbon prevents the formation of Si-C precipitates during solidification at the interface with the ribbon. Thus, a kind of "sandwich" ribbon composed of silicon-carbon-silicon is formed. The layered ribbon is then laser cut, simultaneously on the two faces, in order to obtain the desired dimensions. In the following step, the carbon substrate is removed by heating the tri-plate above the carbon vaporization temperature. The obtained silicon layer is finally scoured to get the RST plate as shown in Fig. 4.

Due to the drawing effect, the grains have a predominant dimension in the drawing direction (often length greater than 50 mm, width lower than 6mm, see Fig. 4). Even if the sample surface has an appearance of orange peel, one can easily observe that some grains have numerous twinning, covering the entire surface of the grain. The thickness of the produced silicon wafers depends of the drawing velocity, the considered ones have an average thickness of 90 µm. Micro-graphs have shown that the thickness is not uniform along the plate edge and can vary locally in the range ± 15% (see the thickness profiles in Appendix A.).

One can assume an inherent texture of the elongated grains with respect to the drawing direction. Thus, EBSD measurements were performed to investigate the crystallographic orientations of the RST grains. The analyzed area was the central part of the plate