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Correlating internal stresses, electrical activity and defect structure on the micrometer scale in EFG silicon ribbons

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ABSTRACT

In the present paper, we study the influence of defects through their stress fields on the electrical activity and residual stress states of as-grown edge-defined film-feed (EFG) multicrystalline silicon (mc-Si) ribbons. We apply a combination of micro-Raman spectroscopy, electron beam induced current, defect etching and electron backscatter diffraction techniques that enables us to correlate internal stresses, recombination activity and microstructure on the micrometer scale. The stress fields of defect structures are considered to be too small (several tens of MPa) to influence directly the electrical activity, but they can enhance it via stress-induced accumulation of metallic impurities. It is commonly found that not all recombination-active dislocations on grain boundaries (GBs) and within grains are accompanied by internal stresses. The reason for this is that dislocations interact with each other and tend to locally rearrange in configurations of minimum strain energy in which their stress fields can cancel partially, totally or not at all. The outcome is a nonuniform distribution of electrical activity and internal stresses along the same GB, along different GBs of similar character as well as inside the same grain and inside different grains of similar crystallographic orientations. Our work has implications for developing crystal growth procedures that may lead to reduced internal stresses and consequently to improved electrical quality and mechanical stability of mc-Si materials by means of controlled interaction between structural defects.

1. Introduction

EFG silicon ribbon growth technology has been developed as a cost-effective alternative to ingot- and block-cast crystal growth technologies due to its low silicon consumption. The silicon ribbons are grown directly from the melt at the desired thickness and cut in wafers by a laser without saw-induced kerf losses [1]. Future directions towards even a more cost-efficient EFG technology include a reduction in the tube thickness t, an increase in the tube face width w and in the growth speed [1–3].

These developments are hindered by the thermally induced stresses characteristic for the EFG silicon growth. They are produced by (1) the steep vertical temperature gradients of $\sim 1000\,^{\circ}\mathrm{C\,cm^{-1}}$ at the melt–crystal interface needed to accommodate the latent heat of crystallization, (2) the curvature of the crystallization front, (3) the mechanical constrains due to continuity of displacements imposed at the tube edges, and (4) the rapid cooling [1,2,4]. Since the temperature gradients vary as t^{-2}, they increase with decrease in tube thickness leading to an increase in the thermal stresses acting on the tube [2]. Above the brittle–ductile transition temperature of silicon, these stresses can relax partly or totally during ribbon growth by plastic deformation including in-plane creep, out-of-plane buckling and the formation of extended lattice defects such as dislocations, low-angle grain boundaries, cracks and their combinations. Below this temperature, the remaining thermal stresses are incorporated as thermally induced residual stresses in the EFG tube [2,3,5]. In particular, the critical stress for buckling, which is proportional to $(t/w)^2$ limits both the decrease in the tube thickness and the increase in the tube width [2,5]. Thermal stresses are also limiting the growth speed [2]. Another important constraint in the EFG growth of stable thinner silicon tubes is the thickness variation of

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up to ± 30 μm across the face width as a result of small horizontal temperature differences of the order of 1–2 °C along the meniscus region [2,6].

Moreover, the grown-in thermally induced residual stresses combined with an unfavorable arrangement of crystal defects having their own stress fields, their superposition is referred to as internal stresses, may couple critically with external mechanical and thermal loads. This may happen during production and handling of wafers/cells and modules leading to unpredictable breakage and additional defects [7–9]. Therefore, understanding and controlling the internal and external stresses are crucial to ensure the mechanical integrity of the EFG wafers/cells as well as to reduce the density of stress-induced defects, which are commonly recombination active, thus improving both process yields and solar cell efficiencies.

Internal shear stresses in EFG and string silicon ribbons have been found mainly at twin and grain boundaries by infrared photoelasticity method known also as infrared birefringence imaging with a spatial resolution of 5 μm/pixel and a sensitivity of ± 1.5 MPa in the best case [8,10–13]. The micro-Raman technique used in the present study is able to probe very concentrated stress distributions originating from structural defects by scanning point-by-point spectra that can be averaged over larger areas if needed [14,15]. Its depth and lateral resolutions depend on the laser excitation wavelength ranging from μm to nm, while its sensitivity is better than ± 12.5 MPa [16,17]. By comparison, photoelasticity is not able to resolve such stress concentrations but it is much better in probing small thermally induced residual stresses since it integrates the signal over the entire thickness of the sample.

It has been observed that high stressed areas show high electron–hole lifetimes [8,12]. So far such correlated investigations have been performed at large scales. However, our previous studies as well as other studies demonstrate the importance of the local variations in properties for a deeper understanding of the solar silicon materials for higher mechanical stability and solar energy conversion efficiencies [16,18–21].

In this work, we correlate mechanical, electrical, and structural properties of as-grown EFG silicon ribbon material on the micrometer scale. For this purpose, we combine at identical positions micro-Raman spectroscopy for measuring μm-scaled internal stress fields, electron beam induced current (EBIC) for evaluating the recombination activity, defect etching for the optical visualization of surface defects, and electron backscatter diffraction (EBSD) for determining the grain orientations and grain boundary types. Our results are discussed in relation to the EFG crystallization process and the existing studies.

2. Experimental details

Commercially available p-type EFG mc-Si material showing about 15.2% cell efficiency after in-line processing has been investigated in this work. Four pieces were cut from different as-grown wafers (125 × 125 mm, mean wall thickness of 200 μm) originating from various heights or faces of an octagonal EFG tube (see Fig. 1(a)) grown under optimal conditions with a speed of 1 cm/min [3]. Prior to the Raman measurements, the samples surface was evened out by mechanical polishing to ensure stress measurements that are not affected by uncontrolled reflections at rough surface facets. We applied a standard polishing procedure changing gradually from larger to smaller diamond particle sizes with the final polishing step removing most of the previously damaged surface layer and thus leaving the samples in a negligible polishing-induced stress state. After polishing, the samples were Secco-etched [22] for 5 s to make the grain boundaries and dislocations visible. The results presented in this paper are representative for the investigated samples being obtained on a piece of 18 × 20 mm shown in Fig. 1(b), which was cut from the center of an as-grown EFG wafer.

The Raman stress measurements were performed at room temperature in the backscattering configuration using a LabRam HR800 spectrometer from Horiba Jobin Yvon. A He–Ne laser with an excitation wavelength of 633 nm was employed resulting in a

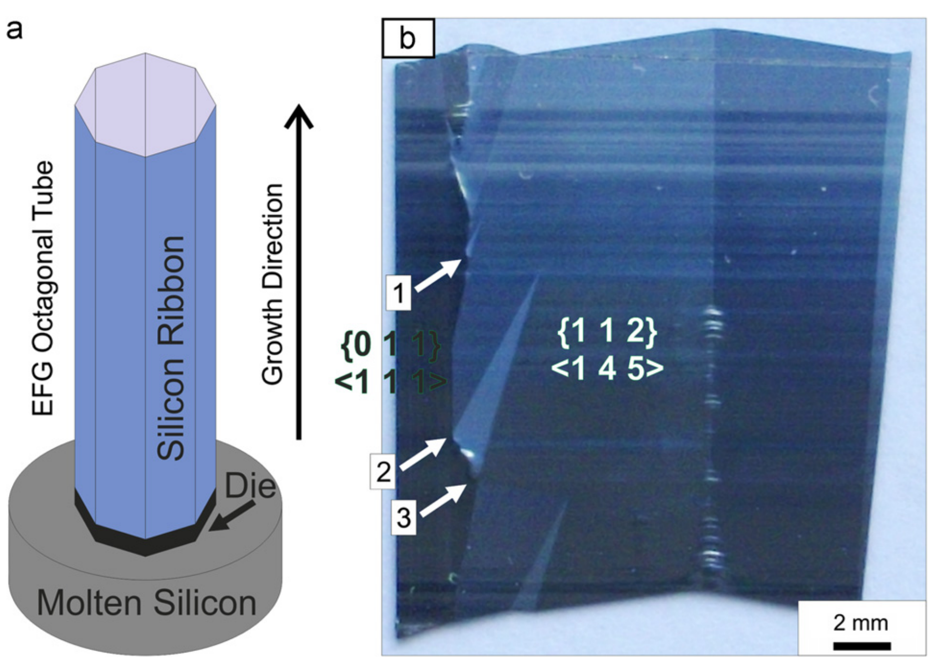

Fig. 1. (a) Schematic of the EFG crystal growth process (not to scale). (b) Optical image of a piece cut from the center of an as-grown EFG wafer. Three representative positions indicated by arrows have been chosen to illustrate the correlation between internal stresses, electrical activity and microstructure. They are situated along a GB that typically occurs between two adjacent grains of {0 1 1} and {1 1 2} orientations characteristic for steady-state EFG growth. The buckling deformation is visible.