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Grain-to-grain contrasts in photoluminescence images of silicon wafers

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Abstract

Photoluminescence (PL) imaging of silicon wafers has become a very valuable characterization technique over the last decade since it is fast, non-destructive and can be applied to finished cells as well as cell precursors. In this contribution, we examine the grain-to-grain contrasts observed in PL images of as-cut, mechanically polished and alkaline textured wafers from multicrystalline (mc) material and material with mono seeds. Understanding the contrasts in PL images of as-cut wafers is of special importance, because PL images of as-cut wafers are used for quality rating and the prediction of final solar cell efficiency. In some cases, grain-to-grain contrasts can dominate the image appearance while their origin remains unclear. Therefore, we investigate the reasons for the observed grain-to-grain contrasts in mc silicon and material with mono seeds. In the as-cut state, the reason for grain-to-grain contrasts is found to be an interplay between different reflectivity of the excitation light and different electrical surface properties. In the mechanically polished state, there are no optical differences between grains and the differences of PL intensity contrasts solely originate from different electrical surface properties whereas for alkaline textured surfaces optical effects are the dominant reason for PL intensity contrasts.

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1. Introduction

Since its introduction in 2006 [1] photoluminescence (PL) imaging has become a very valuable characterization technique in photovoltaics, since it is fast, non-destructive and can be applied to finished cells as well as cell precursors. The understanding of PL images of as-cut wafers from multicrystalline (mc) silicon material [2] is of major importance, because these images can be used for wafer rating and efficiency prediction as suggested in [3,4]. It is an ongoing debate whether efficiency prediction from PL-image evaluation of as-cut wafers is possible. Due to the effect of phosphorous gettering and other high temperature steps on the bulk material quality efficiency

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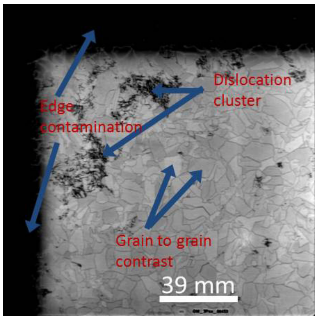
prediction is considered difficult [5]. Nevertheless recent results show good correlation between measured and predicted open circuit voltages by pattern recognition techniques even for unknown manufacturers [6]. Up to now, the major interest was focused on the detection of dislocation clusters, grain boundaries and edge contamination from the crucible, since these are the efficiency limiting defects, but with increasing material quality more subtle features need to be considered. The left part of Figure 1 shows a typical PL image of a mc silicon wafer featuring grain boundaries, dislocation clusters and contamination from the crucible edge. The focus of this work is a fourth contrast feature, which has scarcely been discussed in literature so far: the intensity contrast between different grains.



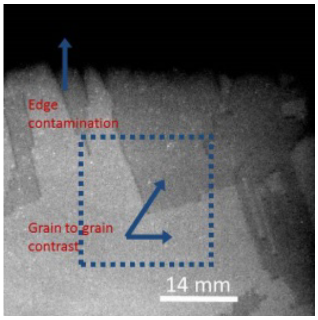


Figure 1: (Left) PL image of an mc-Si wafer. Dislocation clusters, grain boundaries and edge contamination are visible in addition to the grain-to-grain contrasts. (Right) PL image of a Si wafer from material with mono seed. Because of the large grain size, the wafer serves as an excellent object of investigation.

In 2008, Giesecke *et al.* attributed grain-to-grain contrasts in PL images of as-cut wafers to superimposed reflected light from the excitation laser. Nevertheless, due to ongoing improvements of optical filters in the experimental setup, this artifact can be avoided in state-of-the-art measurement setups [7]. Sio *et al.* [8] used grain-to-grain contrasts in polished, unpassivated wafers to deduce grain orientation making use of the fact that the density of SiO_2 – Si interface states between the native oxide and the silicon is different for different grain orientations [9] and discussed the influence of grain orientation on surface passivation in a further work [10]. The danger of misinterpretation of PL intensity contrasts of different grains due to different passivation effects was mentioned by Mtchedlidze *et al.* [11]. Lehmann *et al.* investigated contrasts in PL images of as-cut wafers [12] and attributed these to different bulk lifetimes because of a crystal-orientation-dependent segregation coefficient of impurities, which contradicts to the findings in the present work. In the present work, we give an overview on the reasons for grain-to-grain contrasts in PL images of as-cut wafer, mechanically polished wafers and alkaline textured wafers. We investigate the reasons for the image contrasts in each state quantitatively on a sample wafer. As an investigation object, we use a wafer from material with mono seeds. In contrast to a conventional mc-Si wafer, this wafer features especially large grains and is hence an excellent object of investigation. A PL image of the wafer in the as-cut state is shown in the right part of Figure 1.

2. Possible theoretical reasons for grain to grain contrasts in PL images of as-cut wafers

If low-level injection is assumed, the local PL intensity φ can be written as proportional to:

$$\varphi \sim \left(1 - R_f(790nm)\right) \int_0^W \Delta n(z) N_a dz \tag{1}$$

Here R_f is the reflectivity at 790 nm, which corresponds to the excitation wavelength in the measurement setup, Δn is the excess carrier density, N_a is the doping density and W is the wafer thickness. The excess carrier density is influenced by bulk lifetime and surface recombination velocities. If bulk lifetime and surface recombination velocities are known, the excess carrier density profile can be calculated analytically [13,14] or numerically [15,16]. From equation (1), we can list the most prominent reasons for PL intensity contrasts: