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Detailed Terms
IMPACT OF DEFECT TYPE ON HYDROGEN PASSIVATION EFFECTIVENESS IN MULTICRYSTALLINE SILICON SOLAR CELLS

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ABSTRACT
In this work we examine the effectiveness of hydrogen passivation at grain boundaries as a function of defect type and microstructure in multicrystalline silicon. We analyze a specially prepared solar cell with alternating mm-wide bare and SiNₓ-coated stripes using laser beam-induced current (LBIC), electron backscatter diffraction (EBSD), synchrotron-based X-ray fluorescence microscopy (µ-XRF), and defect etching to correlate pre- and post-hydrogenation recombination activity with grain boundary character, density of iron-silicide nanoparticles, and dislocations. This study reveals that the microstructure of boundaries that passivate well and those that do not differ mostly in the character of the dislocations along the grain boundary, while iron silicide precipitates along the grain boundaries (above detection limits) were found to play a less significant role.

INTRODUCTION
The introduction of hydrogen in crystalline silicon solar cells is well known to passivate defects and improve overall efficiency [1-3]. Reports have shown that the effectiveness of hydrogen passivation of grain boundaries is directly dependent on grain boundary character and metal contamination [4-7]. However, there is still a lack of microstructural understanding regarding which defects passivate poorly and which ones passivate effectively.

RESULTS
In this contribution we present microstructural studies of a specially design solar cell with bare and SiNₓ-coated regions within the same 12.5 x 12.5 cm² sample. Preparation procedures have been reported elsewhere [8]. The electrical performance was characterized using laser beam-induced current (SR-LBIC) [9] at the University of Konstanz at 833 nm and 910 nm. Figure 1(a) presents an LBIC map taken at 833 nm illustrating regions of high (orange) and low (green) minority carrier diffusion length and Fig. 1(b) shows the same area mapped by electron backscatter diffraction (EBSD) revealing the type of grain boundary under study.

Figure 1. LBIC and EBSD of Sample. (a) LBIC measurements (833 nm wavelength, 10 µm step size). Yellowish stripes correspond to bare regions, while orange stripes are SiNₓ-coated. Black lines correspond to the cell’s metallization. (b) Grain boundary types were identified by electron backscatter diffraction. The regions of interest are labeled A to D.

It is evident from Fig. 1(a) that there is a wide range of responses of grain boundaries to hydrogen introduced during the annealing of the SiNₓ coating (firing). Some boundaries showing strong recombination activity in bare regions are nearly totally passivated. On the other hand, some boundaries show no response to hydrogen, exhibiting almost the same LBIC contrast in bare regions and nitrided regions.
The four regions labeled A, B, C, D in Fig. 1 were selected for further analysis. The selection was made to choose a grain boundary that passes over hydrogenation (random angle (RA), misorientation 43.8°) and a boundary that presents almost no change due to hydrogenation (Σ27a GB, 31.2°). High-resolution LBIC images were taken; and were fit to a previously reported model [10] that outputs values for the effective surface recombination velocity (SRV) of the grain boundary. The SRV for the bare regions of the two selected grain boundaries is the same, 8x10^{5} cm/s. However, after hydrogenation, the Σ27a grain boundary shows almost no reduction of SRV while the RA SRV decreases by 2 orders of magnitude.

Previous studies have shown a strong interdependence between GB recombination activity, GB type [11-12], and the density of metal-silicide precipitates [13]. Based on these findings, synchrotron-based X-ray fluorescence microscopy (μ-XRF) was used to study the same selected regions in order to detect metal silicide nanoprecipitates that could potentially be the cause for the change in SRV. Beamline 2-ID-D at the Advanced Photon Source of Argonne National Laboratory, with a beam of 10 keV X-rays focused to a 200 nm beam-spot size, was used to map the four regions of interest. These maps revealed the presence of Fe-rich particles between 50 nm and two microns in diameter decorating the grain boundaries. These particles are mostly FeSi₂ and are known to be a major source of recombination activity in mc-Si solar cells [14]. Interestingly, the density of Fe particles was found to be similar along the two grain boundaries investigated.

Finally, a look into the dislocations present at the grain boundary by chemical etching [15] revealed that the commonality between grain boundaries that show poor passivation (e.g., Σ27a) is a high degree of disorder (faceting) with a quantifiable number of etch pits along the grain boundary. Detailed results and discussion of these experiments can be found in Ref. 8.

**SUMMARY**

In conclusion, a combination of LBIC, EBSD, synchrotron μ-XRF and defect etching studies have revealed that the characteristics of the dislocations along the boundary could determine recombination activity. Accordingly, the density of countable etch pits could be the principal indicator of post-passivation grain boundary recombination activity. In comparison, Fe-rich precipitate decoration at the spatial resolution found in the study played a less significant role in recombination activity. Potentially, iron point defects or smaller precipitates (below our μ-XRF detection limit) could decorate the dislocations, contributing to their recombination activity. These results point to the importance of efforts to control grain boundary microstructure, including grain boundary type and dislocation density, during the growth and processing of mc-Si solar cells.

**REFERENCES**


