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A Model for Electron-Beam-Induced Current Analysis of mc-Si Addressing Defect Contrast Behavior in Heavily Contaminated PV Material

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***Abstract* — Much work has been done to correlate electron-beam-induced current (EBIC) contrast behavior of extended defects with the character and degree of impurity decoration. However, existing models fail to account for recently observed contrast behavior of defects in heavily contaminated mc-Si PV cells. We have observed large increases in defect contrast with decreasing temperature for all electrically active defects, regardless of their initial contrast signatures at ambient temperature. This negates the usefulness of the existing models in identifying defect character and levels of impurity decoration based on the temperature dependence of the contrast behavior. By considering the interactions of transition metal impurities with the silicon lattice and extended defects, we attempt to provide an explanation for these observations. Our findings will enhance the ability of the PV community to understand and mitigate the effects of these types of defects as the adoption of increasingly lower purity feedstocks for mc-Si PV production continues.**

***Index Terms* — mc-Si, silicon defects, electron beam induced current, EBIC contrast, iron contamination.**

I. INTRODUCTION

EBIC contrast behavior of various types of extended defects, including grain boundaries, stacking faults, and dislocations, have been studied extensively [1-7]. Particular attention has been given to the temperature dependence of the EBIC contrast, as plots of contrast at dislocations (C_d) vs. temperature reveal information about extended defect character and impurity decoration[8-11]. There are several classifications of C_d vs. T behavior that have been previously described[11]. Type 1 behavior is represented by a positive slope and high contrast at room temperature and is related to high concentrations of deep level defects related to impurities and dislocation cores. Type 2 behavior is characterized by a negative slope and light or undetected contrast at room temperature. Light contrast at 300K increasing with decreasing temperature represents defects decorated with metallic impurities in the 10^4 – 10^6 cm^{-1} range and shallow levels associated with strain. Type 2 defects showing little to no contrast at 300K are strain related or have concentrations of metallic impurities less than 10^4 cm^{-1}. Results of previous studies of the EBIC contrast of various extended defects have generally agreed with this model. One study however, revealed a large increase in contrast, for decreasing T, at grain boundaries, showing both high and low contrast at 300K[12]. This behavior was attributed to the increase of the reduced surface recombination velocity associated with the different boundaries. However, experimental data with this trend has only been reported for grain boundaries.

II. EXPERIMENTAL

To formulate an EBIC contrast model addressing the issues associated with heavily contaminated mc-Si material, several samples were selected that were known to have concentrations of impurities that would be higher than the concentrations associated with traditional processing methods. The subject of the study was EG-Si that was intentionally contaminated with metallic impurities in the melt and processed into mc-Si PV cells. An uncontaminated EG-Si mc-Si PV cell was the control. The EBIC measurements were performed on a JEOL 5800 SEM equipped with a cold stage capable of achieving liquid nitrogen temperature.

III. RESULTS

EBIC images for the samples studied are shown in Fig. 1. The defects for which contrast measurement were taken are notated in both the images taken at 300K (a,c,e) and the images taken at 80K (b,d,f) and the results are summarized in Table 1. Figures 1a and 1b correspond to the EG-Si intentionally contaminated with 200ppm Fe in the melt, which is the most heavily contaminated specimen in this study. Two positions (1 and 2) were chosen, representing the traditional type 1 and type 2 room temperature contrasts. The contrast measurements at 80K reveal that both the areas measured exhibited large increases in contrast that deviate from the model. The contrast of the two defects measured from the sample contaminated with 50ppm Fe (Fig. 1c and 1d) does not have the same temperature dependent behavior. Mixed and lightly contaminated type 2 behavior fully describes the defects present in these images. Figures 1e and 1f are from EG-Si not contaminated with any known impurities. The contrast measurements represent type 2 behaviors as expected.

The 200ppm Fe sample also exhibits strong contrast increases in regions not associated with the typical line features. There is no detectable contrast at room temperature, but at 80K the contrast is at levels associated with type 1 behavior. There is also a noticeable increase in contrast of the bulk material in the 50ppm Fe sample. The EG-Si sample did not have increased contrast in the bulk, suggesting that this effect is due to the Fe impurities.

Table 1. Summary of contrast measurements for the locations indicated in Figs. 1a-f.

Position	Contrast at 300K	Contrast at 80K
a,b-1	0.076	0.526
a,b-2	0.206	0.355
c,d-1	< 0.01	0.13
c,d-2	0.07	0.12
e,f-1	0.14	0.15
e,f-2	0.04	0.09

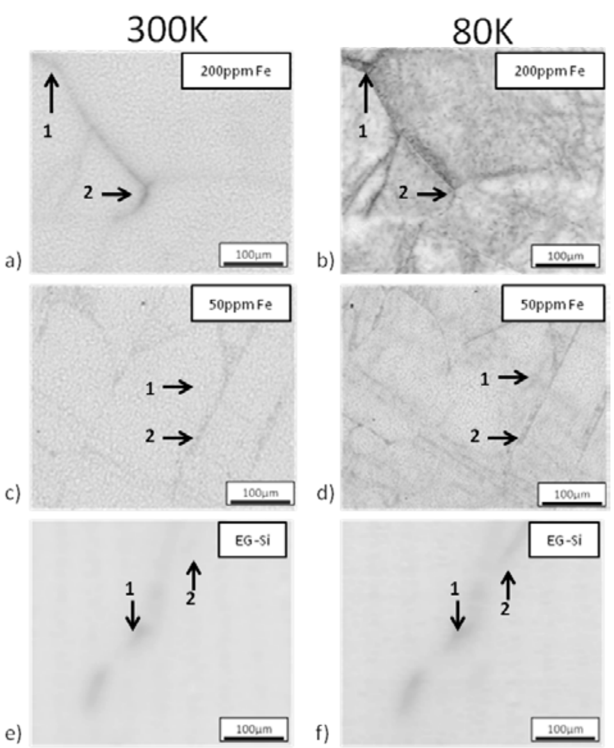

Fig. 1. EBIC images for a) 200ppm Fe sample b) 50ppm Fe sample, and c) EG-Si sample at 300K and 80K with positions for contrast measurements indicated.

IV. Discussion

The EBIC contrast measurements summarized in Table 1 suggest a C_d vs. T relationship that is not fully described by the existing models. Using EG-Si and EG-Si with known concentrations of Fe added to the melt for the measurements suggests a strong dependence of the C_d vs. T behavior on contamination level. Both of the Fe-contaminated samples were taken from the top of a directionally solidified mc-Si ingot, so the concentration of Fe in each sample should be proportional to the amount added. However, the concentration of deep levels would be expected to increase with Fe contamination as the levels induced by Fe in interstitial positions, at grain boundaries and at dislocations, are deep in the bandgap[13]. If this is the case, then very strong contrast at all temperatures should be observed. However, the strongest contrasts are only observed at low temperatures. This behavior is typically understood as relating to the increased activity of shallow levels that become more active in the recombination process as temperatures decrease. However, the magnitude of the contrast increase suggests that another mechanism is responsible.

V. Summary

Based on these results and their reproducible nature, a modification of existing models or a new model of the temperature dependence of EBIC contrast for defects in mc-Si is necessary. This new approach should take into account the observed large increases in contrast at low temperatures in the context of high concentrations of impurities. As the mc-Si PV industry moves toward lower purity feedstock, an EBIC contrast theory tailored to high concentrations of impurities is necessary to provide mc-Si PV producers the opportunity to address the variation in defect behavior associated with heavily contaminated material.

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