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Defect Clusters: Approaches for Overcoming Their Detrimental Impact on Solar Cell Performance

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B. Sopori
National Renewable Energy Laboratory

T. Tan
Duke University

D. Carlson
BP Solar

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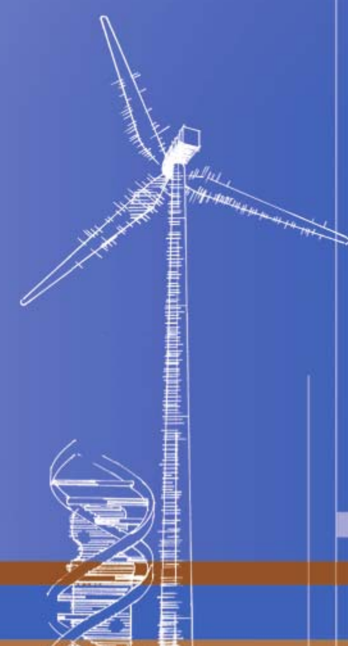

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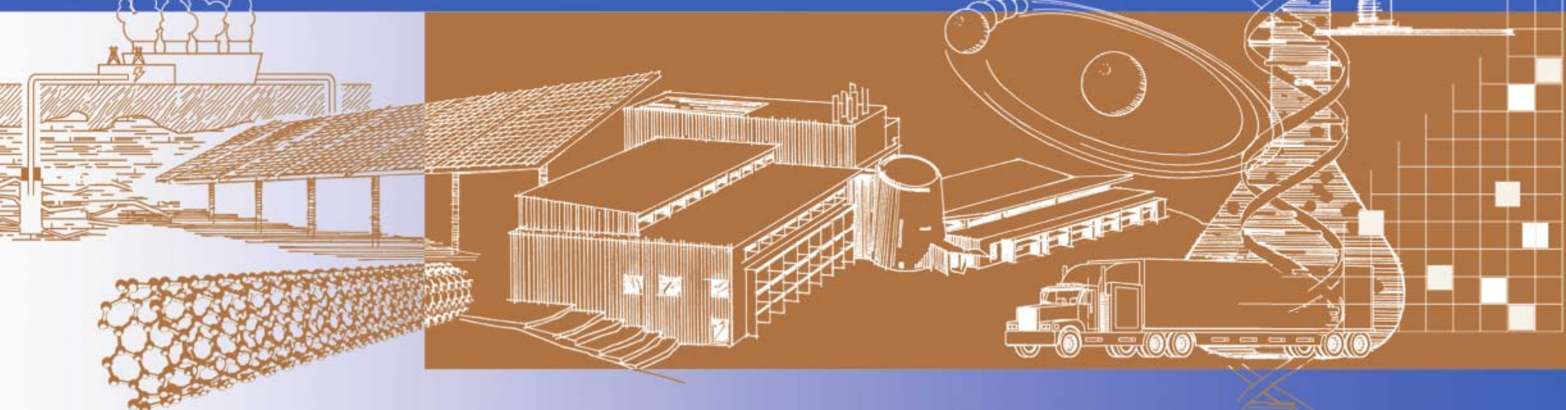

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Defect Clusters: Approaches for Overcoming Their Detrimental Impact on Solar Cell Performance

Bhushan Sopori,[1] Teh Tan,[2] and Dave Carlson[3]
[1] National Renewable Energy Laboratory, [2] Duke University, [3] BP Solar

ABSTRACT

Our analyses show that defect clusters can lower the efficiency of multicrystalline silicon (mc-Si) solar cells by 2 to 4 absolute percentage points. This large loss can be recovered if impurities precipitated at the defect cluster sites can be gettered. We describe a new technique for gettering precipitated impurities.

1. Objectives

Our objective of this work is to establish the limitations set by defect clusters on the solar cell performance and to identify methods that can be commercially applied to overcome these limitations.

2. Technical Approach

Multicrystalline Si wafers contain defect clusters, which are regions of dislocation pile-up and impurity precipitation. The presence of defect clusters in a solar cell produces local shunting and introduces nonuniformities in the cell (see Figs. 1a and 1b). These nonuniformities can greatly degrade the cell performance [1]. To determine quantitatively the influence of defect clusters on the cell characteristics, we performed calculations using our Network Model, and the results were verified experimentally. Furthermore, the modeling was used to predict the performance of solar cells without any defect clusters.

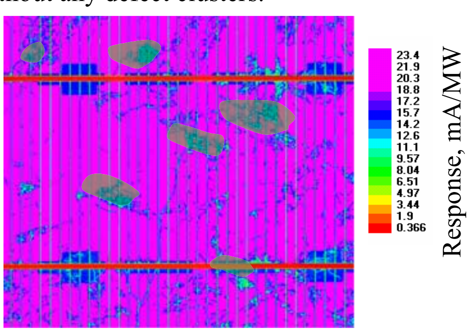

Fig. 1a. A long-wavelength laser-beam-induced current (LBIC) map of a mc-Si solar cell showing defect clusters as regions of low photoresponse.An overlay of the defect map identifies defect cluster regions.

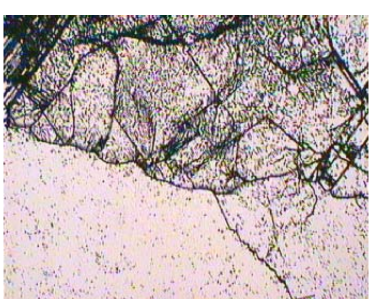

Fig. 1b. A photograph of a defect cluster showing configuration of etch pits produced by Sopori etch.

X-ray micro-analysis of defect clusters shows that the precipitates constitute metallic silicides (see Fig. 2). It is difficult to getter precipitated impurities by standard procedures [2]. We developed a new gettering technique that uses optical processing, with concomitant injection of vacancies, to rapidly dissolve and getter these precipitates.

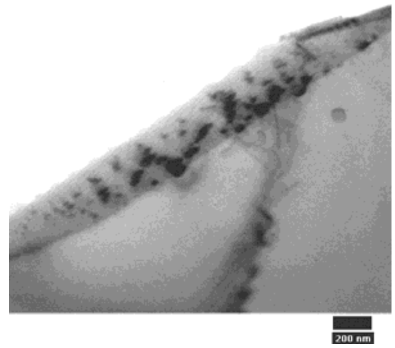

Fig. 2. A photograph showing metal precipitation at a defect cluster site.

3. Results and Accomplishments

3.1. Influence of Defect Clusters on Cell Performance

Sister wafers of commercial mc-Si were split into two groups. One group was defect mapped, and these defect distributions were used in our Network Model to calculate their cell characteristics. The other group of wafers was fabricated into solar cells using commercial processing. Excellent agreement was obtained between theory and experiment. Table 1 shows typical results of measured and calculated cell parameters. It may be pointed out that our calculations only predict an "intrinsic" fill factor, which is higher than one limited by metallization alloying.

Table 1. A comparison of calculated and measured cell parameters. Also shown are the parameters for defect-free cell with the same impurities.

Cell ID	Voc (mV), J_{sc}(mA/cm^2) (Calculated)	Voc (mV), J_{sc} (mA/cm^2) Efficiency (Measured)
#113	580, 29.87	580.6, 27.8, 11.2
#107	601, 30.52	604.7, 30.3, 12.8
No defects	638, 34.00 Efficiency =17.8	

Figure 3 shows calculated current-voltage (I-V) characteirstics of two ceclls in Table 1. Also shown are calculated characteristics of a cell without defect clsusters. Thus, we believe that the efficiency of mc-Si can be improved by 3-4 absolute percentage points if the influence of defect clusters can be removed.

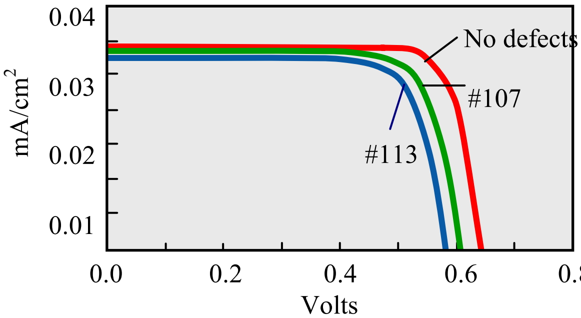

Fig. 3. Calculated I-V characteristics of cells in Table 1.

3.2. Gettering by Optical Processing for Low-Temperature Dissolution and Removal of Precipitated Impurities

Precipitated impurities require high temperatures and long processing times to dissolve, if the dissolution is entirely dictated by the thermal considerations. We have seen preliminary evidence of impurity dissolution at considerably lower temperatures using a combination of optical processing and Al gettering [3]. In this process, the wafer is coated with a layer of Al and then illuminated in a furnace with an optical flux (see Fig. 4). This process results in several favorable mechnisms, which include:

(i) *Temperature increase.* Typically, the optical flux is adjusted to result in a temperature profile sketched in Fig. 4b. In a typical process, the maximum temperature can reach 900°C.

(ii) Increased solubility due to Fermi level effect. Illumination by intense light and the corresponding increase in temperature results in the shifts in the quasi Fermi levels. Because metal impurities can exist both in neutral and charged states, a shift in the Fermi level is accompanied by increased concentration of the charged impurities, which causes an effective increase in the solubility. This effect is very favorable to dissolution of precipitates.

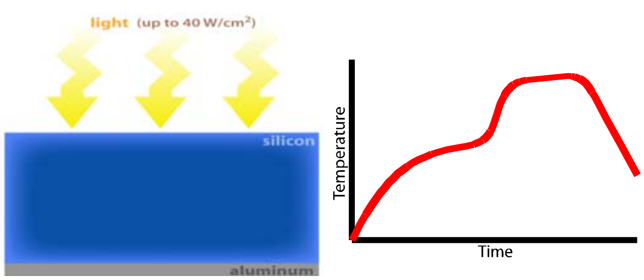

Fig. 4. (left) Schematic of optical processing, and (right) a typical temperature profile for gettering.

(iii) Carrier-enhanced diffusion of metal ions. In an illuminated semiconductor, dynamic charge is exchanged between metal ions corresponding to the following states:

$$M^o + e \Rightarrow M^- \qquad M^- + h \Rightarrow M^o$$

where M^0, M^-, and M^+ represent neutral, negatively charged, and positively charged metal ions, respectively. Because charge exchange occurs via a carrier recombination process, part of the energy released by the charge recombination can be used to overcome the M atom migration barrier. We believe that this charge-enhanced diffusion process can occur for all M species, e.g., to Cu, Ni, and Fe, and can be particularly important for Fe, because solubility enhancement for Fe is expected to be low.

(iv) Vacancy injection. Vacancy injection can occur from a Si-Al interface. Such a mechanism can enhance the dissolution rate of certain precipitates (such as $FeSi_2$, which is known to be the dominant precipitate form). The dissolution rate of a precipitate of radius r is given by:

$$\frac{dr}{dt} = -\Omega_{MSi_x} \frac{C_M^* - C_M}{r} \qquad C_M^* = C_M^{eq} \left(\frac{C_V^{eq}}{C_V} \right)^y \exp\left(\frac{2\Omega_{MSi_x}\sigma}{rk_BT} \right)$$

where:

Ω_{MSi_x} = volume of metal silicide molecule

C_M = actual metal atom concentration in Si matrix

C_M^* = dynamic metal concentration (for constant precipitate size)

C_V^{eq} = thermal equilibrium vacancy concentration in Si

C_V = actual vacancy concentration

C_M^{eq} = equilibrium metal concentration

Y = the misfit factor, defined as the change in local volume of Si matrix corresponding to formation of the precipitate. For example, formation of a $FeSi_2$ precipitate is accompanied by volume shrinkage, with a y value of –0.15. Thus, as can be seen from the above equations, vacancy injection can lead to an enhancement of dissolution rate.

We are performing a variety of experiments to verify the above mechanisms. Initial results have shown a pronounced enhancement of the minority-carrier diffusion length in the defect cluster region, thus indicating precipitate dissolution/gettering.

4. Conclusions

Mitigation of the influence of defect clusters can lead to significant efficiency increase. One approach to achieve this increase is to dissolve the precipitates and simultaneously getter them. Optical processing can lower the temperature and time required to dissolve and getter precipitated impurities. Mechanisms of enhanced dissolution and gettering rates are being investigated.

ACKNOWLEDGEMENTS

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3. B. Sopori, U.S. Patent 6,852,371.

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