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Energy Procedia 27 (2012) 21 – 26

Energy Procedia

SiliconPV: April 03-05, 2012, Leuven, Belgium

Accelerated Light-Induced Defect Transformation Study of Elkem Solar Grade Silicon

M. Tayyib*[a], J. Theobald[b], K. Peter[b], J.O. Odden[c], T.O. Sætre[a]

[a]University of Agder, Postboks 509, NO-4898 Grimstad, Norway
[b]ISC Konstanz, Rudolf-Diesel-Str.15, D-78467 Konstanz, Germany
cElkem Solar AS, Fiskaavn. 100, NO- 4621, Kritiansand S, Norway

Abstract

Solar cells made of silicon feedstock from a metallurgical route must qualify not only the initial efficiency, but must also be comparable to the solar cells made from reference polysilicon on the spectral response after light induced degradation. A detailed comparative study of light induced defects and its impact on cell performance is necessary for both materials. We have studied accelerated light induced degradation (ALID) defect transformation for Elkem Solar Silicon and polysilicon solar cells by selecting wafers from different positions from respective silicon bricks. Active boron-oxygen complexes and iron ions in multicrystalline silicon solar cells have been analyzed, and their impacts on the current voltage characteristics of the solar cells have been studied in detail.

Keywords: Accelerated Light Induced Degradation; Elkem Solar Silicon; Boron-Oxygen Complexes

1. Introduction

The electricity generation from photovoltaics (PV) has increased dramatically in recent years. Over 90% of the PV industry is based on silicon, which is also the major material for the electronics industry. Scientists and industries are working on low cost and energy efficient processes for materials and solar cell fabrication. Solar grade silicon made from the metallurgical route (like the Elkem Solar Silicon – ESS™) is one of the most promising inventions. The material contains a somewhat higher concentration of some elements (especially boron and phosphorus) compared to polysilicon. The solar cells made from ESS™ have shown high efficiencies comparable to standard polysilicon. The long term reliability of such materials is presently undergoing intensive studies in order to prove a 30 year lifespan without significant degradation. The degradation behavior is typically studied in accelerated experiments and compared to

doi:10.1016/j.egypro.2012.07.023

standard polysilicon. In the present work, the accelerated light-induced degradation (ALID) of solar cells made of solar grade silicon made from the metallurgical route by Elkem Solar and standard polysilicon has been studied. Boron-Oxygen complexes and Iron ions in multicrystalline silicon are the major causes of the well-known initial short term device degradation initiated by illumination. ALID causes the fast formation of these complexes within a few minutes which in a normal setting needs much longer time. The amount of these majority carrier trapping sites is essential to calculating the degree of degradation. An advanced surface photovoltage (SPV) mapping technique has been used to calculate boron-oxygen complexes and iron-ion concentration/cm^3 after ALID [1]. It should be pointed out that the initial degradation studied in the present paper is generally not directly relevant for the operation and field degradation of solar modules, since the effect is expected to stabilize very early after the cells are exposed to light.

2. Solar Cell Materials

The concentrations of solute atoms are non-uniformly distributed along the solidification direction of silicon ingots. Consequently, the degradation behavior after light exposure depends on the prior position of the solar cell wafer in the ingot. In this work, we have studied an equal number of PV cells from top and bottom sections of the ingots of the two material qualities, ESS^{TM} and standard polysilicon. The solar cells in both cases are produced from wafers generated by the same ingot/wafer producer using the same industrial size ingot furnace and coming from exactly the same brick positions as source. The solar cells should thereby be considered to be equal in every aspect, except for the feedstock used in the ingot casting. All the cells show high conversion efficiency exceeding 17%.

The solar cells are categorized according to batches.

EB: bottom parts of 100% Elkem Solar Silicon (ESS^{TM}) ingot.
ET: top parts of 100% ESS^{TM} ingot.
PB: bottom parts of 100% POLYSILICON ingot.
PT: top parts of 100% POLYSILICON ingot.

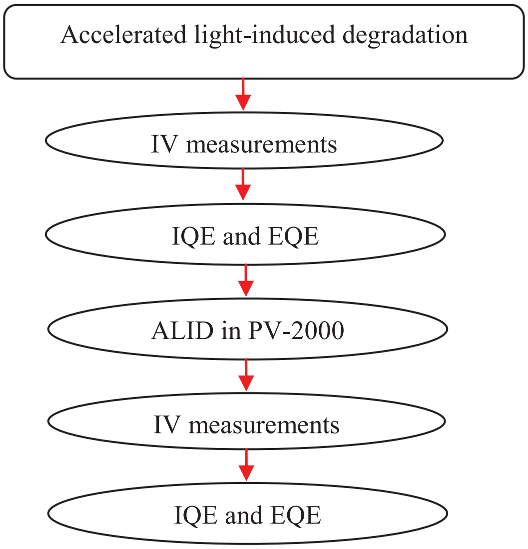
3. Experiment

Degradation measurements of solar cells require a variety of instruments to calculate all required parameters. The I-V measurements before and after ALID are made with a Berger Flasher while the quantum efficiency (QE) is calculated from a standard QE instrument. ALID of all the solar cells is performed in a Semilab SDI PV-2000 instrument, cf. Tables 1 and 2.

The Semilab instrument's working principle is based on the measurement of the diffusion length of minority carriers in the solar cells, before and after ALID, and subsequently calculating the concentration per cm^3 using an AC surface photovoltage (SPV) technique [1]. Incident light on solar cells activates defects in silicon by providing the energy for interstitial oxygen dimmers (O_{2i}) to bond with substitutional Boron, resulting in BO_{2i} formation. At the same time, the incoming light has enough energy to break the electrostatic bond of Fe_i^+-B^- into individual components [2]. Both BO_{2i} and Fe_i^+ are the minority carrier lifetime killers and consequently lowering the conversion efficiency of the solar cells. The ALID experimental sequence is presented in Table 2 and the resultant chemical reactions taking place during each stage are described in Table 1. Combination of light and higher temperatures makes the degradation faster compared to the normal environmental conditions.

The ALID test, in PV-2000, starts with a complete annealing at 200°C followed by an iron recovery step at 90°C, both in the dark, in order to remove any preliminary degradation of the solar cells during handling or storage. This procedure ensures an initial condition of maximum lifetime due to minimization of minority carrier trapping sites i.e. no active BO_{2i} and Fe_i^+ pairs. The accelerated initial light induced degradation (AI-LID) experiments are performed with the standard test conditions described by the Semilab; a second long term accelerated LID test (ALT-LID) is based on somewhat changed conditions with increased illumination time to study the degradation in a more drastic scenario. The detailed description of both ALID tests is shown in Table 2.

Table 1. LID measurements steps (left) and activation/ deactivation steps for defects and resultant chemical reactions in the solar cell(right). *Bold letters indicate lifetime decreasing states



Parameters	Effect*
Annealing	
Temperature $\geqslant$ 200°C	$Fe_iB \rightarrow \mathbf{Fe_i} + B$
Light none	$\mathbf{BO_{2i}} \rightarrow B + O_{2i}$
Time $\geqslant$ 2min	
Fe Recovery	
Temperature 90°C	
Light none	$\mathbf{Fe_i} + B \rightarrow Fe_iB$
Time $\geqslant$ 3min	Boron state unchanged!
LID Activation	
Temperature 120°C	$Fe_iB \rightarrow \mathbf{Fe_i} + B$
Light 1 sun	$B + O_{2i} \rightarrow \mathbf{BO_{2i}}$
Time $\geqslant$ 5min	
Fe Activation	
Temperature 25°C	$Fe_iB \rightarrow \mathbf{Fe_i} + B$
Light 1 sun flash (10x)	Boron state unchanged!
Time 10 x 10s	

Table 2. Measurement mechanism in PV-2000

Step	**Parameters**			**Lifetime**
		AI-LID	**ALT-LID**	
1. Complete Annealing				
1.1 Annealing	200°C	2min	2min	
1.2 Fe Recovery	90°C	3min	3min	max. lifetime
1.3 SPV map		5 mm pitch map		
2. Activating Boron (B)				
2.1 LID Activation	120°C	5min	10min	
2.2 Fe Recovery	90°C	3min	10 min	mid. lifetime
2.3 SPV map		5 mm pitch map		
3. Activating Iron (Fe)				
3.1 Fe Activation	25°C	10x 1 sun flash	10x	
				min. lifetime
3.2 SPV map		5 mm pitch map		

4. Results and Discussion

The ALID was performed on 42 solar cells, two times on each cell, respectively AI-LID and ALT-LID. The same amount of wafers has been used from each material. SPV diffusion length mapping was performed at every degradation state to evaluate the active BO_{2i} and Fe_i^+ concentrations in each sample. The trapping density maps of two randomly selected solar cells from ESS^{TM} and polysilicon are provided in Figures 1 and 2 showing the recombination centers in these solar cells. The plot sequence starts from diffusion length maps of a solar cell leading to concentration of ALID trapping sites as shown in Figure 1. The diffusion length for the non-degraded samples is always higher than the BO_{2i} and Fe_i^+ active state. It was observed that these defects are not localized but rather distributed over the cross section of the solar cell. The defect concentration was calculated by two equations used in the commercial SPV BO_{2i} and Fe_i^+ measuring tool. A detailed description is given in the literature [3]. The concentration of the iron equivalent boron-oxygen does not represent the total amount of B and O in the solar cell, but gives an equivalent value of the active concentration comparable to iron [4]. Figures 1 and 2 make a comparison between AI-LID defects in Elkem Solar Silicon and polysilicon solar cells. In this typical example the concentrations of active trapping sites and decrease in IV parameters of ESS^{TM} solar cell are comparable to the polysilicon solar cell.

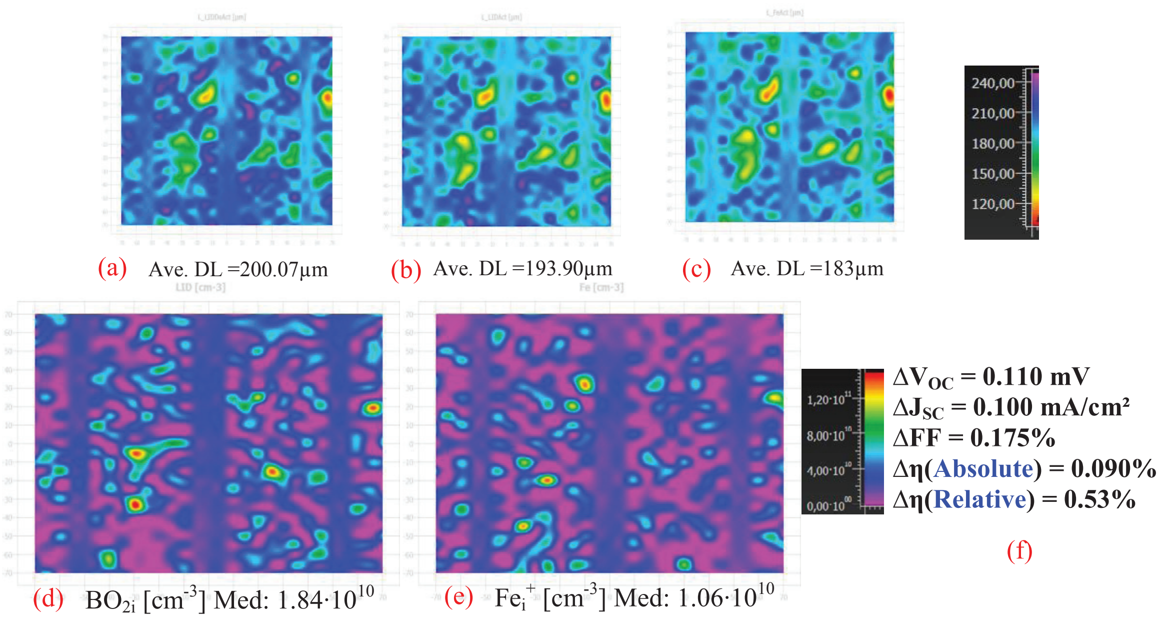


Fig. 1. Diffusion length maps of typical Elkem Solar cells from batch EB during AI-LID (a) LID defects inactive state (b) LID defect active (c) Fe active (d) BO_{2i} concentration map (e) Fe_i^+ concentration maps of degraded solar cell. While the resultant relative changes in IV parameters after AI-LID are presented in (f). The measured diffusion lengths at each stage as well as the median values of LID active defects concentration are mentioned under each map

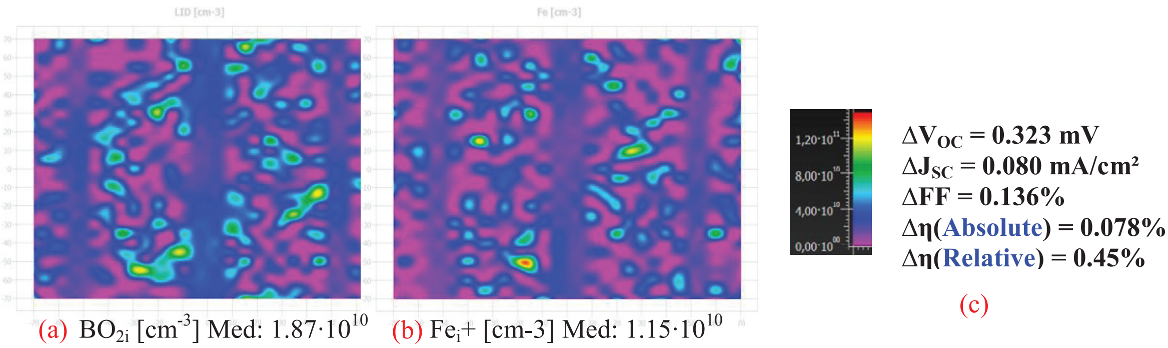


Fig. 2. Defect concentration maps of a typical standard polysilicon solar cell from batch PB showing the distribution of active (a) BO_{2i} (b) Fe_i^+ concentration in the degraded solar cell. The relative changes in IV parameters are also given in (c)

A silicon brick consists of 500 wafers approximately. In our experiment we have chosen 200 wafers from the near bottom part of the ingot as bottom wafers and the same number of wafers from the near top part of the ingot as top wafers. These wafers were further processed by Q-Cells to make solar cells. Furthermore, in our ALID experiment random 42 solar cells were chosen out of a large number of top and bottom cells from each material. Hence, the cells in each batch have not been processed from neighboring wafers. This can be seen as different initial diffusion lengths of each solar cell. The similar results of position dependent diffusion length of solar cells are also previously discussed by K. Peter et al. [5].

The random selection of the solar cells from silicon bricks affects the I-V characteristics as well as the total number of ALID defects. The I-V characteristic parameters measured before and after ALID verify the degree of degradation. For simplicity, all the degradation data are plotted in a box plot so that wider range of results can be shown in one graph. Figure 3 shows the cell efficiency before and after ALID (initial and long term). ALID always causes the decrease in current voltage characteristics of the solar cells due to the fast formation of defects in silicon. AI-LID causes a decrease in cell efficiency with the production of a significant amount of defects. When the ALID conditions are changed from standard to more harsh ones (ALT-LID), a further decrease in cell efficiency is observed. It can be concluded that the trend of decrease in efficiency with the increase in defect concentration look relatively similar in both materials, with little variations due to the random selection of solar cells from the each silicon brick.

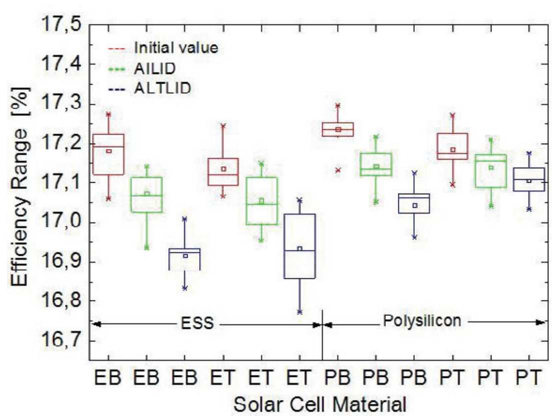


Fig. 3. Box plots of absolute cell efficiency of all solar cells before and after AI-LID and ALT-LID

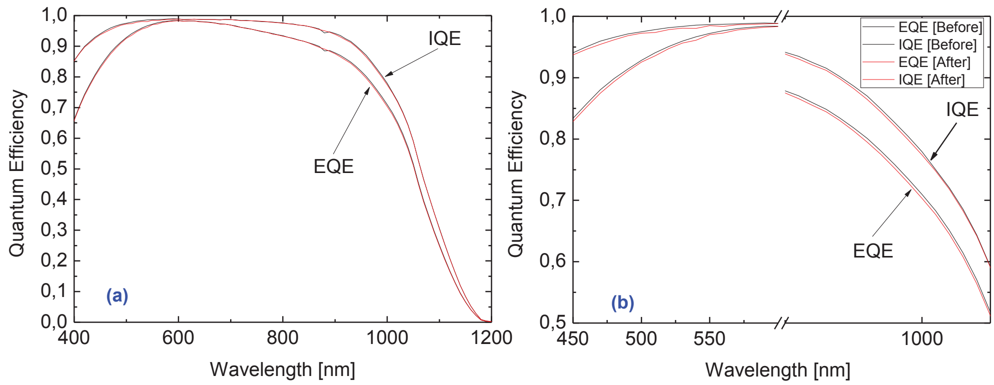


Fig. 4. Quantum efficiency plots of a typical ESS™ solar cell before and after AI-LID. (a) Over the complete wavelength range. (b) Wavelength region near UV and IR are highlighted to show the degree to degradation

A decrease in quantum efficiency (QE), of above mentioned typical ESS™ solar cell, after AI-LID is observed near UV and IR region while it remained almost similar in the region 600 nm < λ < 900 nm. This slight change in QE verifies the decrease of IV parameters before and after AI-LID under standard test conditions. Similar results are obtained for polysilicon based solar cells.

Conclusion

It has been demonstrated that surface photovoltage (SPV) diffusion length mapping of solar cells with two ALID stages enables a detailed investigation of defect transformation mechanisms. The corresponding I-V data and quantum efficiency measured before and after each ALID indicates the performance of both materials in the presence of trapping sites for charge carriers.

When similar batches from both materials were compared, the Elkem material yielded a slightly higher degradation in average during AI-LID. For the Elkem Solar cells, the average decrease in efficiency was approximately 0.6% (relative) with a formation of $\approx 2\cdot10^{10}$ cm^{-3} and slightly $> 1\cdot10^{10}$ cm^{-3} BO_{2i} and Fe_i^+ concentrations respectively after AI-LID. Similar results were obtained for the solar cells from the reference polysilicon, thereby suggesting a solely crucible origin of the iron content. A $\approx$ 0.5% (relative) decrease in efficiency after AI-LID was observed for the polysilicon cells. A little further decline in absolute efficiency is observed after ALT-LID for both materials.

The results found in the present investigation are not statistically representative of commercial output since the research has been limited to one batch only.

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