

## Investigation of the Influence of Deep-Level Defects on the Conversion Efficiency of Si-based Solar Cells

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### ABSTRACT

The influence of deep level defects (DLs) on the conversion efficiency of multicrystalline Si-based standard solar cells (SCs) is investigated. Multicrystalline p-type Si wafers with 156×156 mm dimensions and 200 μm thickness were used for SCs preparation. Three types of SCs with conversion efficiency 10%, 16.8% and 20.4% were studied using capacitance voltage characteristics method (C-V) and by current deep level transient spectroscopy (I-DLTS). The correlation between the total concentration of DLs and the values of the SCs conversion efficiency is found.

### INTRODUCTION

Currently actual questions of increasing the conversion efficiency of solar energy into electricity and reasons of the degradation of solar cells (SCs) are continuously studied. It has got great economic importance and it is important for saving the planet's ecology. The conversion efficiency of SCs depends on the structure of the solar module, the type of semiconductor materials and etc. Certain structural defects with deep energy levels or deep traps in the band gap in active semiconductor layer affect on the stability of SCs electrical properties. DLs are responsible for the generation-recombination processes and form the recombination component of direct current through the p-n junction.

In SCs recombination current leads to reduction conversion efficiency up to 25% [1]. Well known simple equation that explains the relationship of conversion efficiency  $\eta$  of solar energy into electricity is written as equation 1 [2].

$$\eta = \frac{FF \cdot I_L \cdot V_{XX}}{P_{in}} \quad (1)$$

Where FF is the fill factor,  $P_{in}$  is the power of the SC radiation,  $I_L$  is the direct current in the load,  $V_{XX}$  is the open circuit voltage. The load current in the case of n<sup>+</sup>-p-junction consists of diffusion and recombination component [2]. See equation 2.

$$I_L = q \sqrt{\frac{D_n}{\tau_n}} \frac{n_i^2 S}{N_A} \exp\left(\frac{qV}{kT}\right) + \frac{qn_i N_A \sigma(v_T) WS}{2} \exp\left(\frac{qV}{2kT}\right) \quad (2)$$

Where  $q$  is the elementary charge,  $D_n$  is the electron diffusivity,  $\tau_n$  is the electron lifetime,  $S$  is the area of the  $n^+$ -p-junction,  $n_i$  is the intrinsic concentration,  $N_A$  is the shallow acceptor impurity concentration in the p-type base,  $V$  is the bias voltage of SC,  $k$  is the Boltzmann constant,  $T$  is absolute temperature,  $N_t$  is DLs concentration,  $\sigma$  is the capture cross section of charge carriers (CCs),  $\langle v_T \rangle$  is the average thermal velocity of CC,  $W$  is the width of the depletion region. Equations (1) and (2) show that conversion efficiency of solar energy depends on the presence of DLs.

The subject of this work is the analysis of deep level defects influencing on conversion efficiency of SCs based on Multicrystalline silicon (mc-Si) p-n junction. Mc-Si is very promising material for photovoltaic applications and its investigation is a very actual task.

## EXPERIMENT

Boron doped p-type mc-Si wafers of 0.5-2  $\Omega$ -cm resistivity were used to fabricate SCs by n-type 1  $\mu$ m thick layer forming by phosphorus gas diffusion in the Helios-Resource Ltd. The growing method is the directional solidification. Oxygen content  $<1.0 \times 10^{18}$  at/cm<sup>3</sup> was measured by ASTM1188. The antireflection films, front and backside silver contacts were formed also. Standard SC with efficiency coefficient  $\eta = 16.8\%$  (sample #2), defective SC with  $\eta = 10\%$  (sample #1) and SC with anomalous high  $\eta = 20.4\%$  (sample #3) were selected. Samples were studied by C-V at different temperatures (C-V-T characteristics) and I-DLTS techniques. C-V characteristics were performed by Agilent E4980A RLC-meter. The I-DLTS studies were carried out at the measuring complex specially designed for the study of SCs semiconductor diode structures described in [3]. The measuring complex provides the compensation of the leakage current and the measurement of samples with high electrical capacitance. Free holes distribution profiles in the p-type base of the diode structure were estimated from C-V measurements and used for I-DLTS analysis. DLs energy spectra were studied by I-DLTS. DLs concentration was calculated with taking into consideration C-V data. The data about the DLs energy spectra and its parameters such as activation energy, capture cross section, concentration are obtained.

## DISCUSSION

Figures 1-3 demonstrate dark I-DLTS spectra of three SCs measured at the filling pulse voltage width 1 ms and amplitude 0 V and reverse pulse voltage width 10 ms and amplitude -1 V. Therefore the I-DLTS-spectrometer was in registration mode of major carriers' traps. Parameters of obtained DLs such as activation energy  $E_t$ , hole capture cross section  $\sigma_p$  were estimated from Arrhenius plot (see insertions in Figures 1-3) using equation 3 [4].

$$\ln(\tau T_m^2) = \frac{E_t}{k T_m^2} - \ln(\gamma \sigma_p) \quad (3)$$

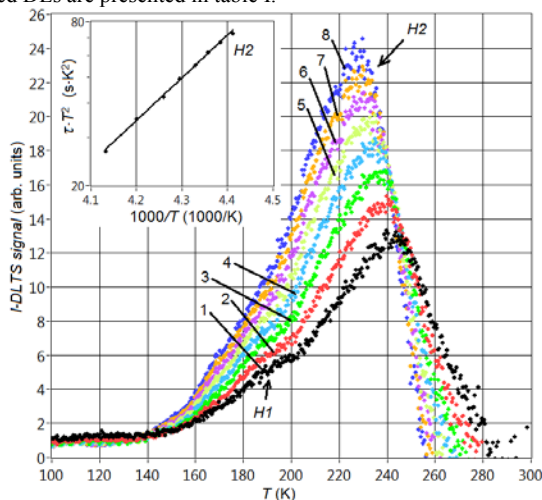
Where  $\tau$  is the relaxation time constant,  $T_m$  is the peak temperature,  $\gamma = 1.78 \cdot 10^{21} \text{ s}^{-1} \cdot \text{cm}^{-2}$  is the pre exponential coefficient for p-Si.

DL concentration was obtained from equation 4 [5].

$$N_t = \frac{2R_{\max}}{qWS} \quad (4)$$

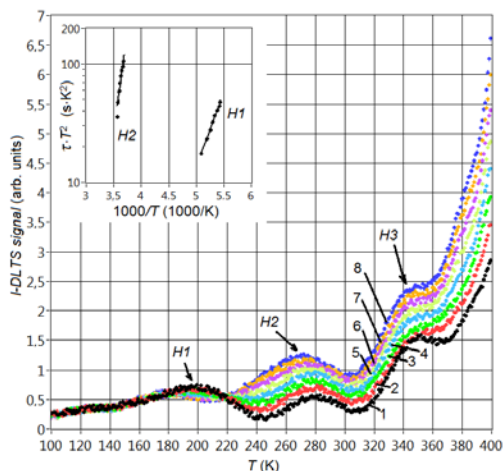
Where  $R_{\max}$  is the height of the corresponding peak on the I-DLTS-spectrum.

Numbering the DLs peaks were taken in the order of their appearance in the I-DLTS spectrum. I-DLTS spectra of the sample #1 contained two peaks, H1 and H2 (see figure 1). The peak H1 was on the shoulder of the peak H2, so its activation energy may be evaluated only by simulation. The nature identification of the DLs was identified with the DLs, previously observed in monocrystalline silicon. An activation energy of H2 peak 0.31 eV was detected. DL H2 is broadened and may be associated with meta-stable B-O defect [6]. In the sample #2 H1 peak with activation energy 0.24 eV was observed at the same conditions that H1 in the sample #1. The hole trap with an activation energy 0.23 eV is a well known divacancy [7]. Parameters of obtained DLs are presented in table I.

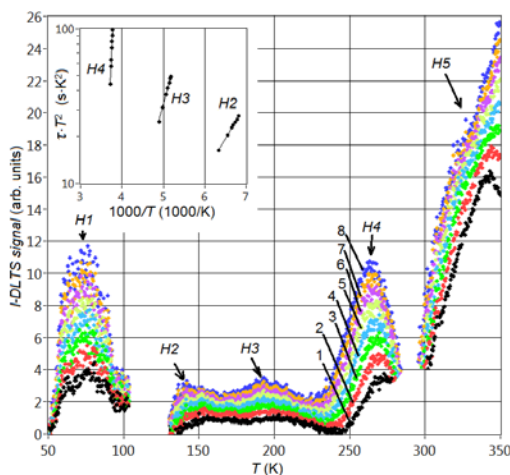


**Figure 1.** I-DLTS spectra of SC with  $\eta = 10\%$  at different relaxation time constant  $\tau$ : 1 – 455  $\mu\text{s}$ ; 2 – 621  $\mu\text{s}$ ; 3 – 771  $\mu\text{s}$ ; 4 – 910  $\mu\text{s}$ ; 5 – 1043  $\mu\text{s}$ ; 6 – 1170  $\mu\text{s}$ ; 7 – 1292  $\mu\text{s}$ ; 8 – 1412  $\mu\text{s}$ . In the insertion the Arrhenius plot is presented.

I-DLTS-spectra of sample #2 contained three peaks. An activation energy of H2 was 0.56 eV. The H2 and H3 peaks positions on the I-DLTS-spectra of sample #2 (see figure 2) were similar to the H4 and H5 peaks positions on the I-DLTS-spectra of sample #3 (see figure 3). The concentrations of DL H3 for sample #2 and DL H5 for the sample #3 were estimated only because that these peaks are hidden behind a sharp increase in the I-DLTS-signal due to the sharp increase of leakage current at high temperatures. For this reason, the nature of these DLs is not completely clear. The temperature peak H1 position in the sample #3 did not depend on temperature at different relaxation time constant. A possible reason of this observation is recharge of surface states.



**Figure 2.** I-DLTS spectra of SC with  $\eta = 16.8\%$  at different relaxation time constant  $\tau$ : 1 – 455  $\mu\text{s}$ ; 2 – 621  $\mu\text{s}$ ; 3 – 771  $\mu\text{s}$ ; 4 – 910  $\mu\text{s}$ ; 5 – 1043  $\mu\text{s}$ ; 6 – 1170  $\mu\text{s}$ ; 7 – 1292  $\mu\text{s}$ ; 8 – 1412  $\mu\text{s}$ . In the insertion the Arrhenius plot is presented.



**Figure 3.** I-DLTS spectra of SC with  $\eta = 20.4\%$  at different relaxation time constant  $\tau$ : 1 – 455  $\mu\text{s}$ ; 2 – 621  $\mu\text{s}$ ; 3 – 771  $\mu\text{s}$ ; 4 – 910  $\mu\text{s}$ ; 5 – 1043  $\mu\text{s}$ ; 6 – 1170  $\mu\text{s}$ ; 7 – 1292  $\mu\text{s}$ ; 8 – 1412  $\mu\text{s}$ . In the insertion the Arrhenius plot is presented.

**Table I.** DLs parameters.

Sample #	$\eta$ (%)	Deep level	$E_t$ (eV)	$\sigma_p$ (cm <sup>2</sup> )	$N_t$ (cm <sup>-3</sup> )	$N_{\Sigma}$ (cm <sup>-3</sup> )
1	10.1	H1	0.25±0.05 (simulation)	—	4.3·10 <sup>15</sup>	1.5·10 <sup>16</sup>
		H2	0.31±0.02	6.3·10 <sup>-17</sup>	1.1·10 <sup>16</sup>	
2	16.8	H1	0.24±0.02	8.7·10 <sup>-17</sup>	8.5·10 <sup>14</sup>	3.4·10 <sup>15</sup>
		H2	0.56±0.02	3.9·10 <sup>-11</sup>	9.2·10 <sup>14</sup>	
		H3	—	—	1.7·10 <sup>15</sup>	
3	20.4	H1	—	—	—	2.5·10 <sup>15</sup>
		H2	0.17±0.02	1.3·10 <sup>-17</sup>	1.1·10 <sup>14</sup>	
		H3	0.21±0.02	2.3·10 <sup>-17</sup>	1.2·10 <sup>14</sup>	
		H4	0.56±0.02	8.5·10 <sup>-11</sup>	4.2·10 <sup>14</sup>	
		H5	—	—	1.8·10 <sup>15</sup>	

For H2 and H3 peaks  $E_t$  were found as 0.17 and 0.21 eV respectively. The DL 0.17 eV may be explained by different ways in different literature references. DL 0.21 eV probably has the same nature as the H1 in the sample #2. The total DLs concentration  $N_{\Sigma}$  was also calculated. The highest total DLs concentration observed in the sample with the lowest  $\eta$ . The DL H1 concentration in the sample #3 was not taken into account in calculation the  $N_{\Sigma}$ . Further analysis of the DLs influence on the conversion efficiency will be associated with the modeling of the influence of each defect separately.

**CONCLUSIONS**

As a result of measurements the correlation between the total concentration of DLs and the values of the SCs conversion efficiency is found. It is found that in a sample with an abnormally high conversion efficiency total concentration of DLs in six times less than in the sample with the lowest efficiency.

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