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Investigation of Deep-Level Defects Lateral Distribution in Active Layers of Multicrystalline Silicon Solar Cells

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ABSTRACT

The influence of deep level defects lateral distribution in active layers of multicrystalline Si-based standard solar cells is investigated. Multicrystalline p-type Si wafers with 156×156 mm dimensions and 200 μm thickness were used for SCs preparation. One type of solar cells with conversion efficiency 20.4% was studied using capacitance voltage characteristics method (C-V) and by current deep level transient spectroscopy (I-DLTS). From various places along the diagonal of solar cell's substrate with 20.4% efficiency nine pieces with an area ~20 mm^2 were extracted and studied. I-DLTS spectra of the five pieces from solar cell were measured. The features of deep levels defects concentration lateral distribution along the SC's surface were studied.

INTRODUCTION

Multicrystalline silicon (mc-Si) based solar cells (SCs) have such advanced technical and economical properties as acceptable lower production cost and relatively high and comparable efficiency of solar energy conversion into electricity to monocrystalline silicon based SCs. Mc-Si is a naturally defective material due to the structural features. The defects or the deep centers (DCs) form deep energy levels (DLs) in the semiconductor band gap. DLs are the centers of free charge carriers recombination. The efficiency of SCs depends on DLs and their parameters such as spatial and lateral distribution and activation energies. In order to optimize the structure and technology of SCs and to obtain advanced parameters it is important to study DLs and their distribution peculiarities.

The correlation between the total concentration of deep traps and the values of the SCs conversion efficiency was found early on the example of three type SCs based on multicrystalline silicon (mc-Si) with different efficiencies 10.1, 16.8 and 20.4% [1]. The main purpose of the work is an investigation of the DL's energy spectrum of defects and their distribution along the active layers of the SCs to improve the undastanding how DL's defects lateral distdibution influences on the SC's efficiency.

EXPERIMENT

Boron doped p-type mc-Si wafer of 0.5-2 Ω·cm resistivity was used to fabricate SC by n-type 1 μm thick layer forming by phosphorus gas diffusion in the Helios-Resource Ltd. The growing method is the directional solidification. Oxygen content <1.0×10^{18} at/cm^3 was measured by

ASTM1188. The antireflection film, front and backside silver contacts were formed also. Standard SCs usually have the efficiency coefficient η = 16.8%, defective SCs have η = 5-10%. Sometimes there SCs with anomalous high η. At present work the SC with η = 20.4 % was selected for an investigation. Samples were pieces with areas 2-10 mm^2 that cleaved from different parts of the SC's substrate surface (see Figure 1).

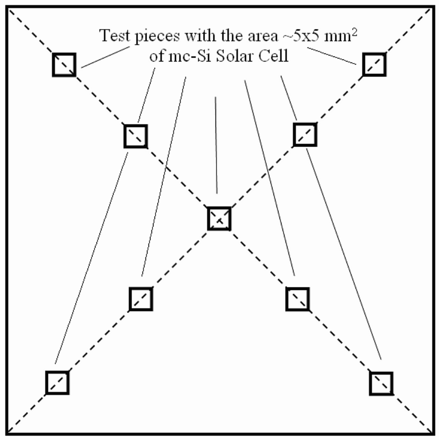

Figure 1. The scheme of test nine pieces with an area ~20 mm^2 which were cleaved from places along the diagonals of SC's substrate.

Samples were studied by C-V methode at different temperatures (C-V-T characteristics) and I-DLTS techniques. C-V characteristics were performed by Agilent E4980A RLC-meter with option 001 at temperatures 100 – 350K and at fixed frequencies in the range 1 kHz – 1 MHz. The closed type helium cryostat Janis CCS400/204N was used as the measuring cell. The traditional DLTS method [2] based on measuring the electrical capacitance relaxation is not quite suitable for investigation of DLs in SCs. The I-DLTS method of studying the electric current relaxation is more suitable. A specially designed measuring system that allow to measure I-DLTS-spectra of barrier structures and SCs characterized by high leakage current, large area of the p-n-junction and relatively large electrical capacitance was used for investigation of the DLs parameters [3]. The measuring complex provides the compensation of the leakage current and the measurement of samples with high values of an 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.

I-DLTS spectra were measured in DL's recharge mode by applying a pulse voltage. The amplitude of the filling pulse voltage was chosen close to open circuit voltage of the SC. At this condition DLs in the active layer where electron-hole pairs are generated and recombined during SC operation are recharged. Detected DLs were hole traps with activation energies in the range 0.17-0.56 eV. The peculiarities of DL's lateral distribution of concentration were analyzed.

DISCUSSION

C-V characteristics were measured at bias voltage –5 to +1 V and amplitude of test signal 25 mV. In Figure 2 typical C-V characteristics measured at RT of the three samples from SC with η = 20.4 % with maximum deviation of capacitance values in coordinates $1/C^2$ (C is the capacitance per unit squire) versus applied voltage are shown. It should be noted that for a reverse bias (it is not shown in the Figure 2) up to –2V the linear character of dependencies was observed. The free hole concentration was estimated from the slope of linear part of C-V curves in the figure 2. It is changed from $1.1 \cdot 10^{15}$ cm^{-3} to $1.2 \cdot 10^{15}$ cm^{-3} with changing the test signal frequency from 1 kHz to 1 MHz. From the C-V characteristics of all test samples the homogeneous distribution of free hole concentration along the SCs surface was found.

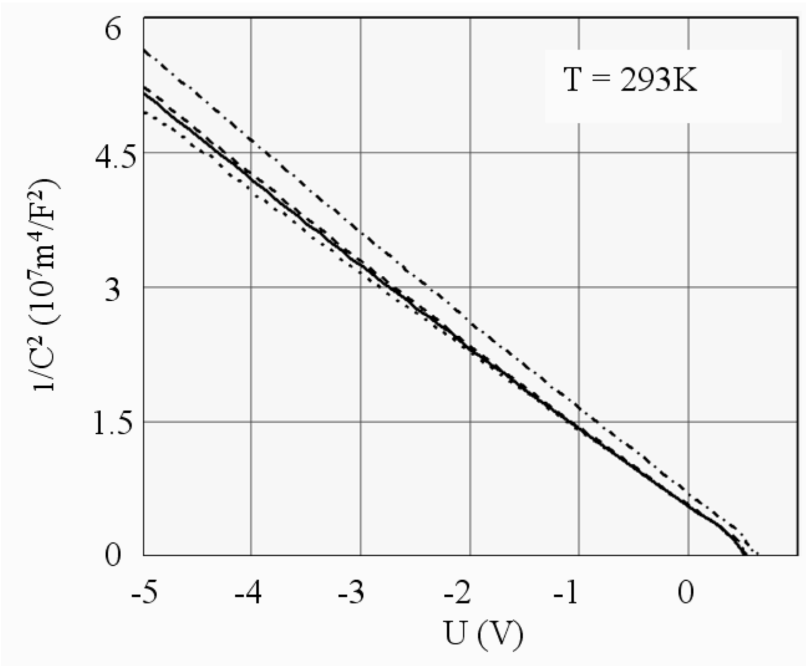

Figure 2. C-V characteristics of mc-Si based SC measured at room temperature and frequencies of 1 kHz (dotted line), 10 kHz (solid line), 100 kHz (dashed line) and 1 MHz (dash-and-dot line).

Typical I-DLTS spectra of the full SC with η = 20.4 % are presented in Figure 3. I-DLTS-spectra of full SC contained five peaks. Numbering the DLs peaks were taken in the order of their appearance in the I-DLTS spectra. The nature identification of the DLs was identified with the DLs, previously observed in monocrystalline silicon. Parameters of obtained DLs are presented in table I. 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 the hole trap or well known divacancy with an activation energy 0.23 eV [4]. An activation energy of H4 was 0.56 eV. 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. The concentration of DL H5 was estimated only because that this peak is 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 this DL is not completely clear. The total DLs concentration $N_{t\Sigma}$ was also calculated. The DL H1 concentration was not taken into account in calculation the $N_{t\Sigma}$.

In the Figures 4 and 5 a typical I-DLTS spectra of the sample cleaved from the central part and from the edge part of the SC with η = 20.4% respectively are presented.

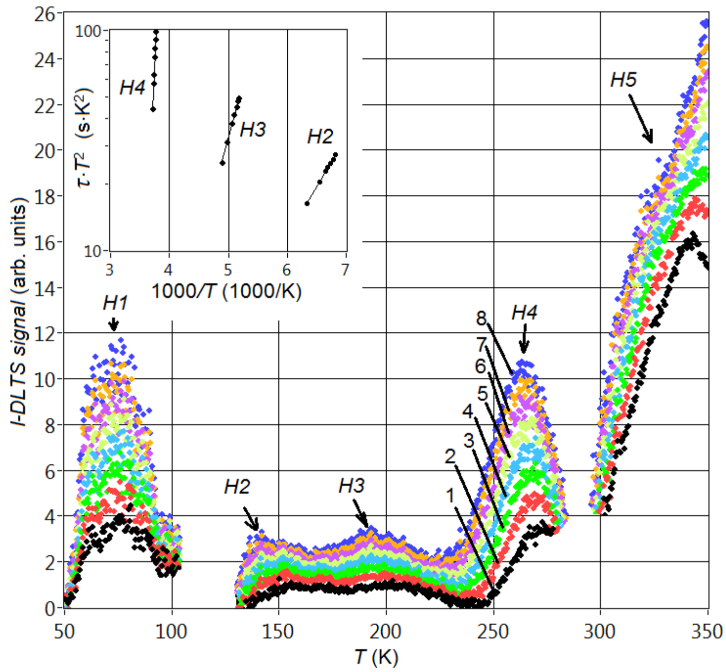

Figure 3. I-DLTS spectra of the full SC with η = 20.4% at different relaxation time constant τ: 1 – 455 μs; 2 – 621 μs; 3 – 771 μs; 4 – 910 μs; 5 – 1043 μs; 6 – 1170 μs; 7 – 1292 μs; 8 – 1412 μs. In the insertion the Arrhenius plot is presented.

It is obvious that the I-DLTS spectra of the separate cleaved samples are very different from the integrated spectra of the full solar cell. I-DLTS spectra of the sample cleaved from the central part of the SC has very broadened peak H6 that has an estimated activation energy 0.68 eV. The use of this value due to the strong peak broadening can not be a reliable way to identify the nature of this peak. I-DLTS spectra of the sample cleaved from the edge part of the SC contained two dominated peaks H7 and H8. The peak H7 was broadened, and on the left low temperature side one or more peaks is viewed. The DL corresponding to the peak H8 has an extremely high value of the capture cross section. The formally calculated activation energy exceeds half of the silicon band gap. This may be due to the strong temperature dependence of the hole-capture process. The height of the peaks was estimated values of concentrations, the maximum of which turned out to be of the same order with the total concentration of DLs obtained from the integral I-DLTS spectra of full SC. The physical origin of the DLTS spectra difference between the central part and the edge of mc-Si SC is due to the distribution of structural defects in the substrate which are due to features of the existing mc-Si substrate growth technology. Defects are the recombination centers of generated charge carriers, so they reduce SC conversion efficiency. Mc-Si is more defective material than monocrystalline Si. It makes clear the origin of low efficiency of mc-Si SC.

Thus, the correlation between the I-DLTS spectra of separated parts of the solar cell on the example of nine samples from different parts of the solar cell substrate is not found. Apparently, this may be because the dimensions of silicon microinhomogeneities are substantially smaller than those of cleaved samples. Further investigations will be aimed an increasing the localization of the electrophysical properties study of the sample so that the size of the region under investigation does not exceed the typical dimensions of the mc-Si microcrystals. Further analysis of the DLs influence on the conversion efficiency will be associated with the modeling of the influence of each defect separately.

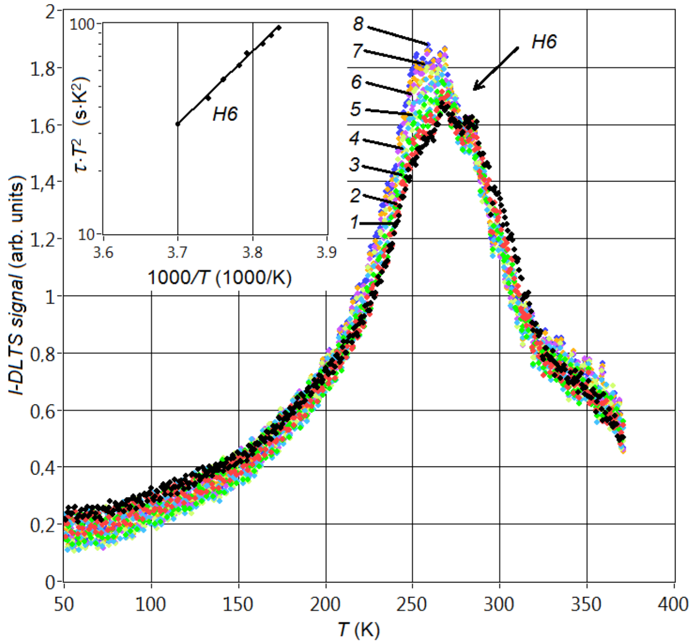

Figure 4. I-DLTS spectra of the sample cleaved from the central part of the SC with η = 20.4% at different relaxation time constant τ: 1 – 455 μs; 2 – 621 μs; 3 – 771 μs; 4 – 910 μs; 5 – 1043 μs; 6 – 1170 μs; 7 – 1292 μs; 8 – 1412 μs. In the insertion the Arrhenius plot is presented.

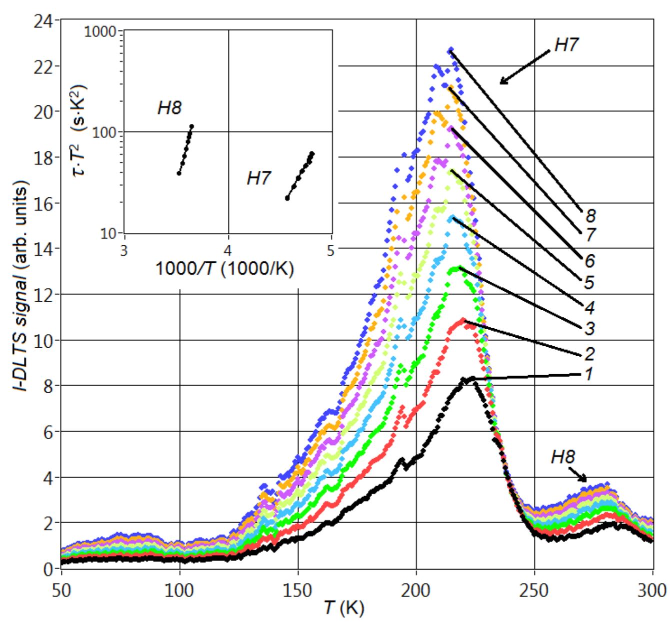

Figure 5. I-DLTS spectra of the sample cleaved from the edge of SC with η = 20.4% at different relaxation time constant τ: 1 – 455 μs; 2 – 621 μs; 3 – 771 μs; 4 – 910 μs; 5 – 1043 μs; 6 – 1170 μs; 7 – 1292 μs; 8 – 1412 μs. In the insertion the Arrhenius plot is presented.

Table I. DLs parameters.

Sample #	Deep level	E_t (eV)	σ_p (cm^2)	N_t (cm^{-3})	$N_{t\Sigma}$ (cm^{-3})
Full SC η = 20.4%	H1 H2 H3 H4 H5	– 0.17±0.02 0.21±0.02 0.56±0.02 –	– $1.3\cdot10^{-17}$ $2.3\cdot10^{-17}$ $8.5\cdot10^{-11}$ –	– $1.1\cdot10^{14}$ $1.2\cdot10^{14}$ $4.2\cdot10^{14}$ $1.8\cdot10^{15}$	$2.5\cdot10^{15}$
sample cleaved from the central part of the SC	H6	0.68±0.03	$5.1\cdot10^{-11}$	$1.2\cdot10^{14}$	
sample cleaved from the edge of SC	H7 H8	0.36±0.03 0.75±0.03	$2.7\cdot10^{-15}$ $2.1\cdot10^{-10}$	$2.8\cdot10^{14}$ $1.7\cdot10^{15}$	

CONCLUSIONS

The energy and concentration of deep level defects localized in mc-Si were measured. The deep-level defects lateral distribution in the active layer of multicrystalline silicon solar cells was investigated. The correlation between the I-DLTS spectra of separated parts of the solar cell on the example of nine samples from different parts of the solar cell substrate is not found. But the correlation between the total DL's concentration in the active layer of mc-Si SCs and conversion efficiency was found early in our previous work [1]. The ways of further research are outlined.

ACKNOWLEDGMENTS

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