ELECTRICALLY ACTIVE DEFECTS IN SOLAR CELLS BASED ON AMORPHOUS SILICON/CRYSTALLINE SILICON HETEROJUNCTION AFTER IRRADIATION BY HEAVY Xe IONS

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The contribution is focused on the diagnostics of structures with a heterojunction between amorphous and crystalline silicon prepared by HIT (Heterojunction with an Intrinsic Thin layer) technology. The samples were irradiated by Xe ions with energy 167 MeV and doses from $5 \times 10^8 \, \mathrm{cm}^{-2}$ to $5 \times 10^{10} \, \mathrm{cm}^{-2}$. Radiation defects induced in the bulk of Si and at the hydrogenated amorphous silicon and crystalline silicon (a-Si:H/c-Si) interface were identified by Deep Level Transient Spectroscopy (DLTS). Radiation induced A-centre traps, boron vacancy traps and different types of divacancies with a high value of activation energy were observed. With an increased fluence of heavy ions the nature and density of the radiation induced defects was changed.

K e y w o r d s: silicon HIT solar cell, amorphous-crystalline silicon heterostructure, DLTS measurement, high-energy heavy Xe ions irradiation, radiation hardness

1 INTRODUCTION

Solar cells based on silicon heterostructures belong to highly prospective photovoltaic devices. Significant advancement in the development of heterostructures with hydrogenated amorphous silicon, a-Si:H, and crystalline silicon, c-Si, has been achieved by the heterojunction with a thin intrinsic layer technology (HIT) [1]. The reason is in its simplicity, low costs and higher efficiency at higher temperatures in comparison with the conventional cells [2]. The charge flow through the HIT structure is strongly affected by the defects in the substrate and by the traps at the interface between amorphous and crystalline silicon [3]. In spite of the achieved results, the mechanism of charge carrier transport through such an interface and mutual relationships between technological and physical parameters and their impact upon the short-circuit current and open-circuit voltage of the final solar cell still have not been explained satisfactorily [4]. The most recent and comprehensive knowledge of the preparation and characterization of solar cells based on amorphous and crystalline silicon was reported in [5]. Relatively little is known on the radiation resistance of solar cells. From the practical point of view, stability and functionality of solar cells are strongly linked with the concentration and electrical activity of radiation defects [6].

Intentional implementation of electrically active defects into HIT structures by heavy ion irradiation gives the possibility to analyse the generation-recombination processes related to the photovoltaic phenomenon. Generally, semiconductor devices exposed to an extremely harsh type of radiation show incorrect functionality [7]. Formation of radiation-induced defects in the a-Si:H/c-Si heterostructures irradiated by high energy heavy ions has a particular influence on their electrical parameters.

The contribution presents the results of the study of electrically active defects on the Al/a-Si:H(n)/a-Si:H(i)/c-Si(p)/Al structures irradiated with high doses of 167 MeV Xe ions by capacitance DLTS method, capacitance as a function of frequency, and current-voltage measurements in dependence on temperature.

2 EXPERIMENTAL

The a-Si:H(n) 50 nm/a-Si:H(i) 5 nm/c-Si(p) 525 μm structures were fabricated on high-quality $\langle 111 \rangle$-oriented p-type silicon doped by boron at a concentration of $1.6 \times 10^{21} \, \mathrm{m}^{-3}$. The thickness of Si wafers was 525 μm. Prior to deposition, the surface of the silicon wafer was cleaned in a solution of HF. In the next step, a-Si:H(i) with a thickness of 5 nm was deposited. The samples were finalized by deposition of 50 nm thick a-Si:H(n) to form a heterojunction emitter. The layers of amorphous silicon doped by phosphorous as well as of the intrinsic silicon were deposited by plasma enhanced chemical vapour deposition (PECVD) in the Laboratory of Photovoltaic Materials and Devices, TU Delft in the Netherlands. Subsequently, the structures were irradiated with heavy Xe

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Table 1. Summary of experimental data from the DLTS measurements

Trap	Sample	Energy ΔE_{T} (eV)	Cross-section σ_{T} (cm^2)	Concentration N_{T} (cm^{-3})	Probable origins of deep energy levels
T1	AB0	0.09	–	–	-interface of a-Si:H(n)/c-Si(p) [6]
T2	AB0	0.18	1.7×10^{-16} for n	1.7×10^{13}	- interface of a-Si:H(n)/c-Si(p) [6], - 0.234 Zn-2(for n)
T3	AB0 AB3	0.29	7.0×10^{-17} for n 1.3×10^{-18} for p	2.0×10^{13}	- 0.320 Ti-dd or 0.330 Pt-d (for n) - Fe-5(for p)
T4	AB0	0.37	2.0×10^{-16} for n 1.0×10^{-16} for p	2.0×10^{13}	- 0.417 Cu-a (for n) - 0.360 Ag (for p)
T5	AB1 AB2	0.13	4.2×10^{-17} for n 8.0×10^{-17} for p	1.4×10^{13}	- radiation defect - (A center), - vacancy-oxygen complex [7]
T6	AB1	0.32	1.5×10^{-15} for n 3.0×10^{-15} for p	1.0×10^{13}	- radiation defect (for p) - vacancy-boron $E_{\mathrm{v}} + 0.3 - 0.45$ [8]
T7	AB2	0.43	1.4×10^{-16} for n 2.0×10^{-16} for p	3.5×10^{13}	- radiation defect, - 0.429 Fe-d (for p)
T8	AB2	0.54	2.9×10^{-17} for n 5.7×10^{-17} for p	1.0×10^{13}	- radiation defect
T9	AB3	0.61	3.4×10^{-15} for n 1.8×10^{-15} for p	1.8×10^{12}	- radiation defect, - 0.599 eV Zn-aa, 305-000, xr

ions with energy 167 MeV in the Joint Institute for Nuclear Research, Dubna, Russia. The samples with irradiation fluences 5×10^8cm^{-2} (AB1), 5×10^9cm^{-2} (AB2), 5×10^{10}cm^{-2} (AB3) and non-irradiated control sample (AB0) were investigated.

For current and capacitance characterization, a top emitter contact was prepared by evaporation of a 100 nm thick aluminium layer with various photolithographically patterned areas of the gates. The bottom contact was created by evaporating a full area aluminium contact onto the back side of silicon.

I–V measurements were carried out using a source-meter unit Keithley 612A in temperature range from 300 to 400 K. Solar simulator 16S-002-300 with spectrum AM1.5 was used as a source of illumination. Impedance spectroscopy (IS) realized through measurements of capacitance as a function of temperature was performed using an LCR meter AGILENT 4284A and a nitrogen cryostat system.

Deep levels and electrically active traps were identified by the capacitance DLTS. Measurements were carried out in the temperature range from 85 to 375 K using the BIORAD DL8000 measuring system equipped with the Fourier transform analysis of the measured capacitance transients, Deep Level Transient Fourier Spectroscopy (DLTFS). DLTFS is a digital system that records the whole capacitance transients. It has significant advantages over both the rate window and lock-in amplifier types of measuring systems in terms of a higher sensitivity and a better deep level energy resolution. During measurements, the reverse bias was set at different voltages and periodically pulsed to the fill voltage for trap filling. The obtained DLTS spectra were evaluated using the Fourier transform analysis by "Direct auto Arrhenius single evaluation".

3 RESULT AND DISCUSSION

The measured DLTS spectra were obtained by applying identical measurement parameters: pulse width $t_{\mathrm{p}} = 5.12$ ms, period width $T_{\mathrm{W}} = 5$ ms, reverse bias voltage $U_{\mathrm{R}} = -0.5$ V and pulse voltage $U_{\mathrm{p}} = 0.05$ V at temperatures from 85 to 375 K and then the traps were evaluated by simulation of the particular parameters. The correlation curves together with the Arrhenius graphs with particular parameters are shown in Fig. 1. The calculated activation energy parameters ΔE_{T}, cross section σ_{T}, and defect concentration N_{T} are summarized in Tab. 1.

Analysis of the non-irradiated sample AB0 showed a high value of volume defects in the Si substrate (T3, T4) which correspond to the metallic impurities Fe, Cu and Pt. The traps (T1, T2) are located in the interface between amorphous and crystalline silicon, which confirmed the results of original DLTS measurements [8]. On the samples irradiated with various Xe fluences deep levels were detected which correspond to the electrically active defects due to destruction from the implanted Xe heavy ions in both the amorphous and crystalline regions of the heterostructure. The deep levels can be characterized as radiation induced defects of different types of divacancies, or as vacancy-impurity bonds.

The samples with lower fluences (AB1, AB2) exhibited a typical A-center defect [9], vacancy-oxygen (T5) in the vicinity of the a-Si:H(n)/c-Si(p) interface. A radiation defect vacancy-boron $E_v + 0.3 - 0.45$ eV reported in [10] was with high probability also present (T6) in the investigated samples with lower fluences (AB1). The high fluence of Xe ions (AB3) suppressed the existence of trap T5, however, with strong conservation of the original deep level trap T3 in the bulk of c-Si(p). Traps T7, T8 a T9 with high activation energies were detected at high fluences (AB2, AB3), unfortunately, without exact deter-
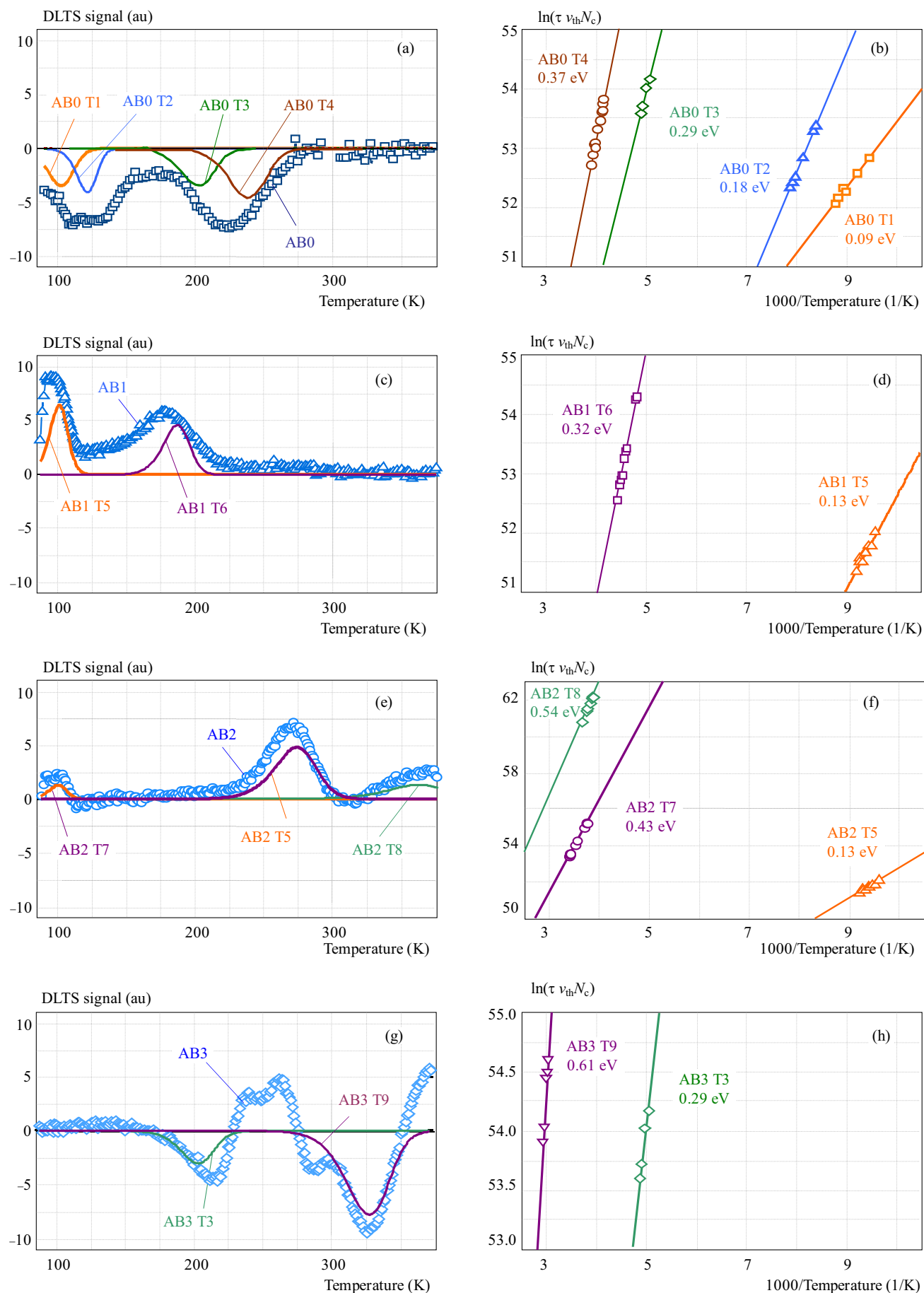
Fig. 1. The measured and simulated DLTS spectra (left) and calculated Arrhenius plots (right) of nonirradiated AB0 and; irradiated AB1, AB2 and AB3 samples
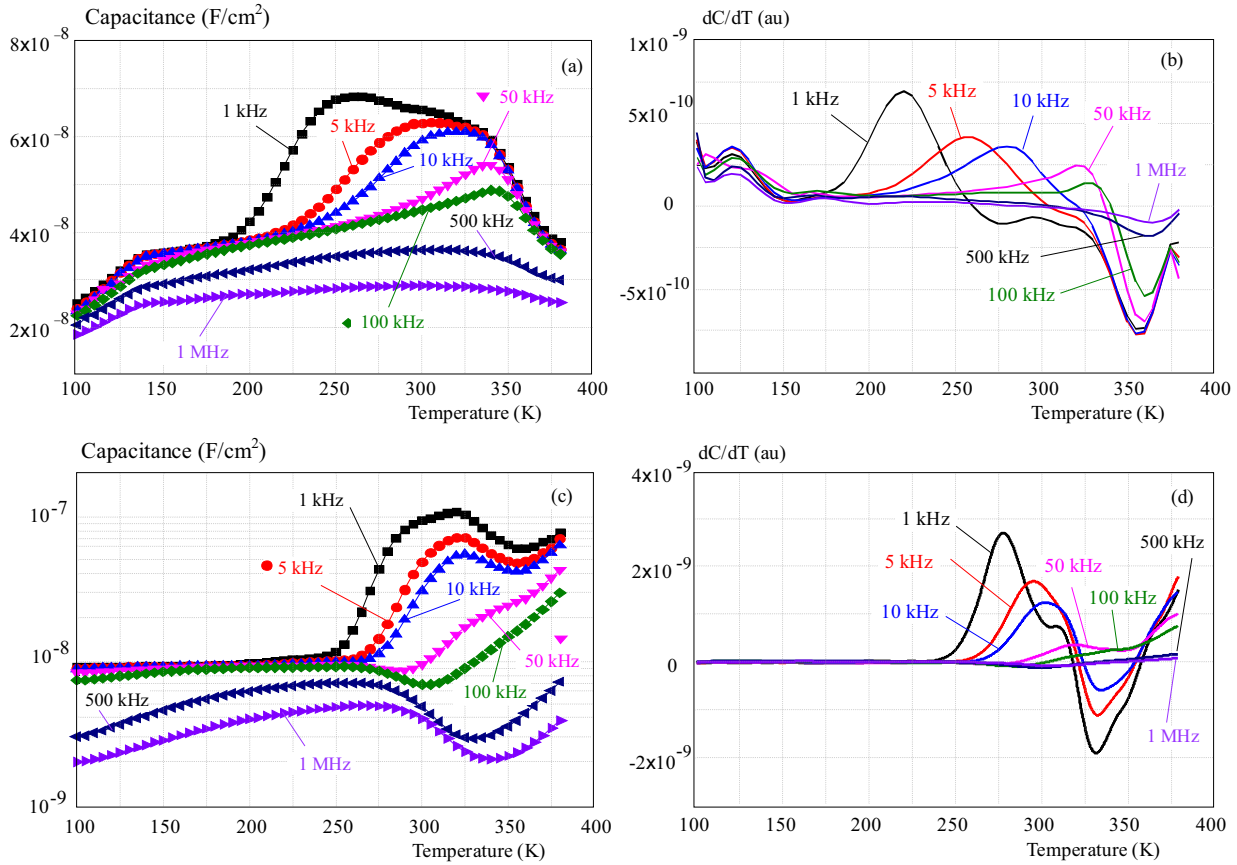
Fig. 2. The measured capacitance as a function of temperature of the reference: (a) — non-irradiated sample AB0, (c) — the strongly irradiated sample AB3, and (b),(d) — their derivatives

mination of their type. The measured correlation curves were obtained at higher temperatures. It is supposed that these are deep levels localized in the forbidden band of a-Si:H(n) and at the interface. Exacting analysis of the process of charge carrier capture-emission at the deep levels was influenced by the complexity of interaction of the electrically active defects by annihilation of the newly formed radiation induced defects with the original ones within the a-Si:H(n)/c-Si(p) structure.

Impedance spectroscopy (IS) was applied to further investigate the traps in samples AB0 and AB3. The results of capacitance as a function of temperature for various AC frequencies of the measurement signal are shown in Figs. 2(a) and 2(c) for samples AB0 and AB3, respectively. The obtained curves were differentiated and plotted as a function of temperature, Figs. 2(b) and 2(d).

After differentiation, marked peaks are observed on the curves measured with different frequencies of the measurement signal. From the temperatures of peak maxima and from the measurement frequency it is possible to construct the Arrhenius plots. Figure 3a shows the obtained Arrhenius plots which reveal traps with activation energies 0.23 eV and of 0.61 eV for samples AB0 and AB3, respectively. The activation energy 0.23 eV is close to the value of 0.18 eV obtained by DLTS, thus the defect can be identified as trap T2. We assume that this trap is related to defect states at the a-Si:H/c-Si interface. The

activation energy 0.61 eV obtained from IS analysis for sample AB3 is identical with trap T9 identified by DLTS and represents a deep level trap which corresponds to radiation defect or Zn trap (see Tab. 1).

The effect of the traps on the performance of solar cell structures AB0 and AB3 was analysed by measurements of temperature dependent current-voltage (I–V–T) characteristics under solar simulator. Since only a round metal gate was used as a top electrode, it is not possible to extract the real output parameter and efficiency of the solar cell structure. However, the temperature change of measured parameters can provide valuable information about the properties of the structure. For the purpose of this study, the I–V–T characteristics were measured to observe the temperature dependence of the open-circuit voltage (V_{OC}) that is defined by the equation [11]

$$V_{OC} \approx \frac{E_{ar}}{q} - \frac{n_{id}kT}{q} \ln \frac{J_{00}}{J_{SC}},$$

where E_{ar} is the activation energy of recombination, which has a dominant impact on the solar cell performance, n_{id} is the ideality factor, J_{00} is the saturation current density and J_{SC} is the short-circuit current density. The activation energy E_{ar} can be determined from the linear interpolation of V_{OC} *vs* T. The intersection of this curve with the vertical axis ($T = 0$ K)
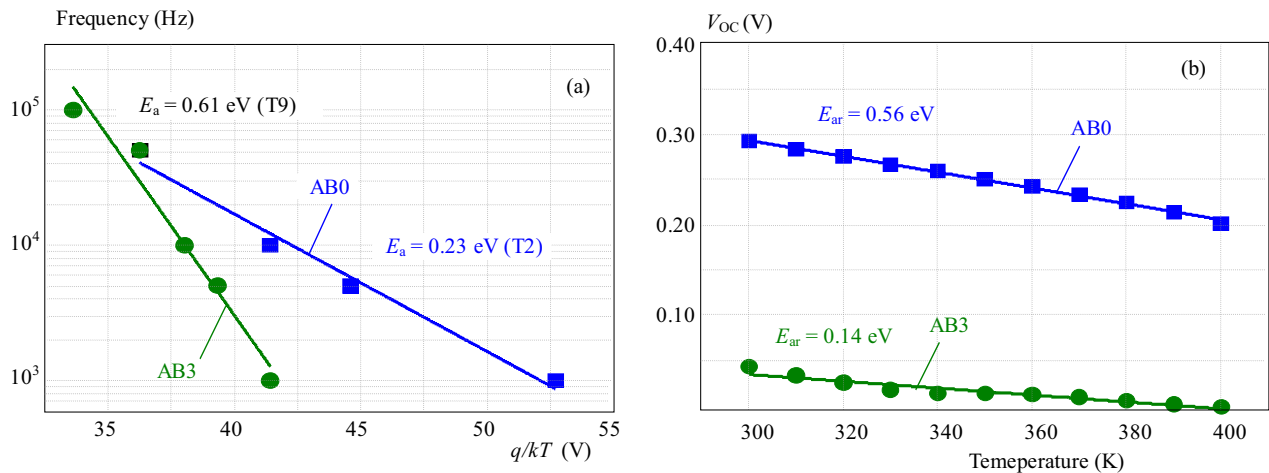
Fig. 3. (a) — Arrhenius plots obtained from the peaks of the derivatives of the temperature dependent capacitance, (b) — open-circuit voltage (VOC) as a function of temperature for samples AB0 and AB3

is equal to E_a/q. Figure 3b shows the extracted values of V_{OC} obtained from temperature dependent I–V–T measurements under light for samples AB0 and AB3. The irradiated sample AB3 exhibits a strong decrease of V_{OC} (~ 50 mV at 300 K) compared to non-irradiated sample AB0 (~ 300 mV at 300 K). For sample AB0 the activation energy is $E_{ar} = 0.56$ eV. The dominant recombination path for the solar cell structure with high performance is the bulk recombination and E_{ar} for such a solar cell is equal to the band gap of the absorption layer. In our case, however, the value of E_{ar} is approximately a half of the Si band gap (1.12 eV). It is important to underline that the activation energy obtained from V_{OC}–T is an integral value which represents the dominant recombination path rather than the energy of a particular trap in the structure. Thus we assume that the dominant recombination path in structure AB0 is recombination in the space charge region or in the vicinity of the interface or directly at the interface. In the light of this conclusion, it is possible to justify trap T2, identified by both DLTS and IS, as a trap with its origin at the heterointerface.

The strongly irradiated sample AB3 exhibits a low activation energy of the dominant recombination path, $E_{ar} \sim 0.14$ eV (Fig. 3(b)). Such a low activation energy is probably related to the defects at the interface or in the amorphous layer and pointed out at a strong disorder of the amorphous layer after irradiation, which causes recombination of photogenerated electrons.

4 CONCLUSION

In samples irradiated by high energy heavy Xe ions, many deep levels of electrically active defects were detected in the space charge region of the heterojunction of amorphous and crystalline silicon by capacitance DLTS and IS measurements. Defects corresponding to metallic impurities in the bulk of c-Si(p) and defects at the a-Si:H(n)/c-Si(p) were observed in the non-irradiated sample. The dominance of the interface traps was confirmed

by both of the capacitance methods employed. The nature of radiation defects varied markedly with the fluence of the implanted Xe ions. Comparison of the spectroscopic measurements confirmed the dominant effect of radiation defects in the space charge region with deep levels and high activation energies.

The effect of electrically active defects on the photovoltaic performance was further investigated be means of temperature dependent I–V curves measured under illumination. The sample irradiated by a high dose of Xe ions exhibited a lower open circuit voltage and a lower activation energy of dominant recombination path. The drop of the activation energy is related to a higher activity of the traps at the interface of amorphous and crystalline silicon and of the radiation defects in the amorphous part of Si.

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