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Radiation hardness investigation of heterojunction solar cell structures with TCO antireflection films

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Abstract. Phosphorus doped silicon carbide film as emitter in heterojunction structure was deposited on p-type Si(100) wafers at various deposition conditions by means of PECVD technology using silane (SiH_4), methane (CH_4), hydrogen (H_2) and phosphine (PH_3, 2 vol.% in H_2) gas as precursors. ITO or IZO film was RF magnetron sputtered on top of the different P doped a-SiC:H(n) film. Irradiation of structures with Xe ions to total fluency $5x10^{11}$ cm^{-2} was performed at room temperature. Influence of phosphorus concentration and type of transparent conducting oxide was investigated. A deeper insight on the impact of irradiation on the electrophysical properties of sample was obtained by the analysis of complex impedance spectra.

1. Introduction

Silicon heterojunction solar cells with amorphous silicon carbide emitter are attractive roads for further cost reduction of solar cells, owing to significant low consumption of raw silicon material and a low temperature deposition. Employing a-SiC:H film as an intrinsic layer of single junction solar cell, open-circuit voltage as high as 0.99 V has been achieved [1]. A p-i-n-type proto-crystalline silicon (pc-Si:H) multilayer solar cell fabricated by employing a silicon–carbide double p-layer structure and a layered structure of multilayer processing through alternate H_2 dilution was investigated [2]. Amorphous silicon carbide is an excellent alternative passivation layer material for silicon solar cells especially for performance in hard and space environment. Higher band gap (1.8 – 2.3 eV) of amorphous SiC layers (compared to a-Si:H) lead to a lower parasitic light absorption [3]. A p–i–n amorphous silicon (a-Si:H) solar cell with high-conversion efficiency is presented via use of a double p-type window layer composed of microcrystalline silicon and amorphous silicon carbide [4]. The electrical and optical properties of p type hydrogenated amorphous silicon carbide (a-SiC:H) are compared with p-type hydrogenated amorphous silicon (a-Si:H) widely used as emitter material of silicon heterojunction solar cells [5]. Introduction of the low temperature plasma sources for Si photovoltaic applications and discussion of the effects of low-temperature plasma dissociation and

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deposition of Si-based thin films was reported [6]. The influence of the substrate temperatures on the properties of ITO films, which are deposited by rf-magnetron sputtering, and hence on the performance of the mentioned heterojunction solar cells was already reported [7]. DC reactively sputtered IZO thin films were studied after incorporating hydrogen by depositing them in the presence of hydrogen in the plasma as well as by post-annealing of IZO films in hydrogen [8]. Authors focused on the diagnostics of structures with a heterojunction between amorphous and crystalline silicon prepared by HIT (Heterojunction with an Intrinsic Thin layer) technology. Their samples were irradiated by Xe ions. Current and capacitance measurements revealed the effect of radiation defects induced in the bulk of Si and at the a-Si:H/c-Si interface upon the electro-physical properties of the structures [9].

2. Experiment

Phosphorus doped silicon carbide film as emitter in heterojunction structure was deposited on p-type Si(100) wafers at various deposition conditions by means of PECVD technology using silane (SiH_4 -10 sccm), methane (CH_4 -3 sccm), hydrogen (H_2 -100 sccm) and PH_3 (2.0 vol.% in H_2, 15-30 sccm), gas as precursors. Transparent conductive oxide (TCO) as ITO (indium oxide/tin oxide 90/10 wt.%) or IZO (indium oxide/zinc oxide 90/10 wt.%) films were RF magnetron sputtered on top of the different P doped a-SiC:H(n) films.The thickness of the deposited ITO or IZO films was kept at 100 nm. Concentrations of elements in the ITO and IZO films were analyzed using RBS and ERD analytical method simultaneously [10]. Photolitography and lift off technique were used for preparation of the Al grid as a top contact of SC structure on the antireflection films. Al ohmic contact was made on the back side of the Si substrate. Al contacts were prepared by vacuum thermal evaporation. Figure 1 shows the main technological steps of prepared heterojuction solar cell structure.

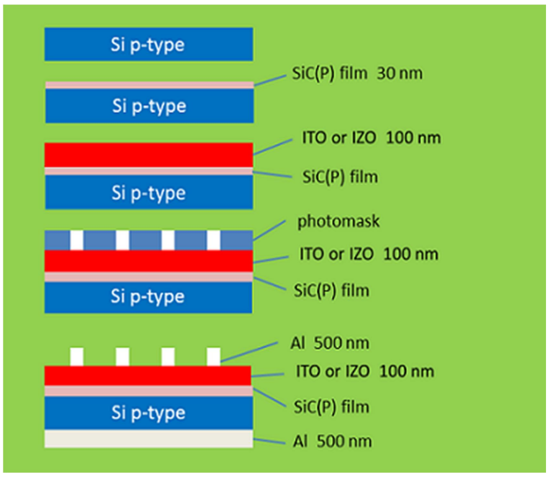


Figure 1. Technological steps utilized for the preparation of heterojunction solar cell structures.

Irradiation of structures with Xe ions to total fluency $5x10^{11}$ cm^{-2} was performed at room temperature in the IC100 accelerator at JINR, Dubna. Impedance spectra were measured by the Agilent LCR Meter 4284A.

3. Results and Discussions

Figure 2a shows RBS spectra of ITO film and shows leading edge at about 810-820 ch, corresponding to In and Sn, leading edge at 520 ch, corresponding to Si and feature corresponding to oxygen is

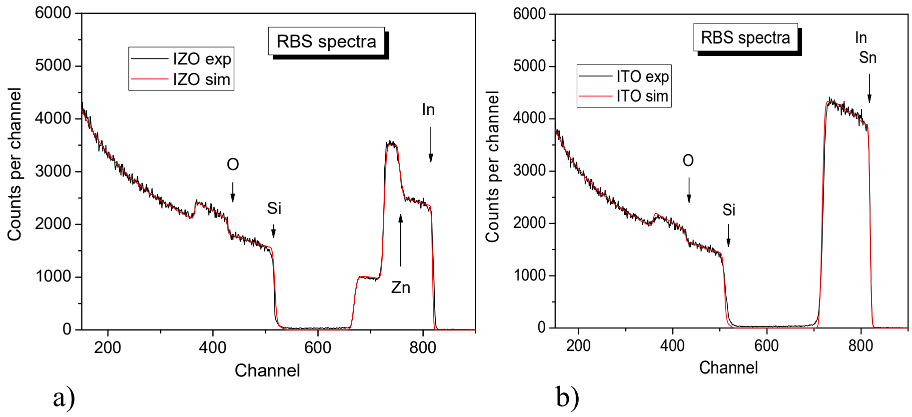


Figure 2. Experimental and simulated spectra RBS for a) ITO and b) IZO antireflection films prepared by RF magnetron sputtering.

observed on the profile of bulk Si with leading edge at 430 ch. Figure2b shows RBS spectra of IZO film and shows leading edge at 820 ch, corresponding to In, leading edge at 760 ch, corresponding to Zn, leading edge at 520 ch and 430 ch, corresponding to Si and oxygen, respectively. Calculated concentrations using simulated spectra RBS and ERD was for ITO (indium-17.5 at.%, tin-17.5 at.%, oxygen-62.5 at.%, hydrogen-2.5 at.%) and IZO (indium-17.5 at.%, zinc-15.5 at.%, oxygen-64.5 at.%, hydrogen-2.5 at.%). We proposed that hydrogen in the films was originated from the wall of magnetron sputtering chamber.

The AC impedance measurements of the prepared heterostructures were performed at DC voltage bias –600 to 700 mV in the dark to monitor the behavior of the prepared structures before and after Xe irradiation. An example of selected impedance spectra – Nyquist characteristics measured on samples coated with ITO or IZO films are shown in figure 3 and 4. Obtained impedance spectra show typical behavior in complex plane. More detailed analysis using simulation program and fitting procedure of the measured data has shown that impedance plot is in fact a superposition of two semicircles. These two semicircles represent two different relaxation processes. The significantly reduction of shunt resistance (diameter of the circles) for reverse DC biases due to irradiation is clearly recognizable in figure 3 and 4. On the other hand, in the case of the DC bias voltage in the forward direction shunting resistance increased after irradiation for both types of samples.

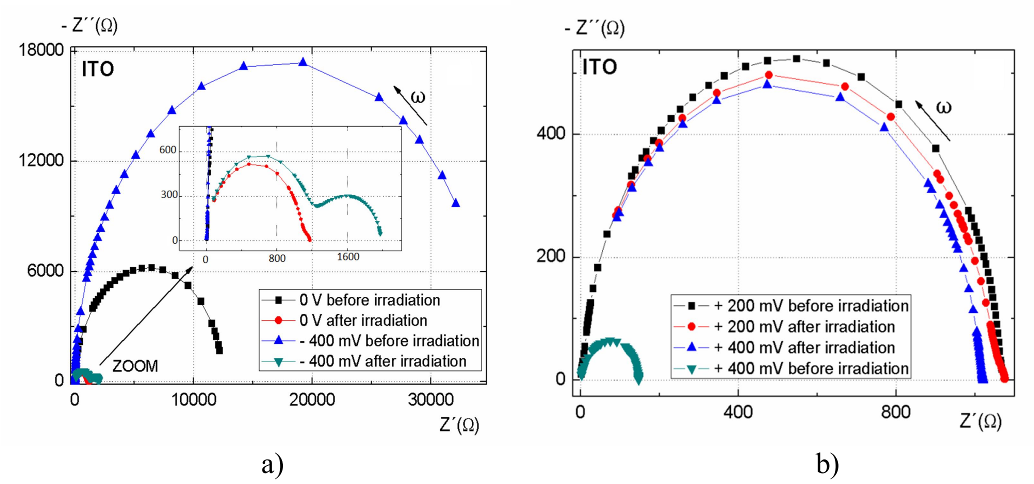
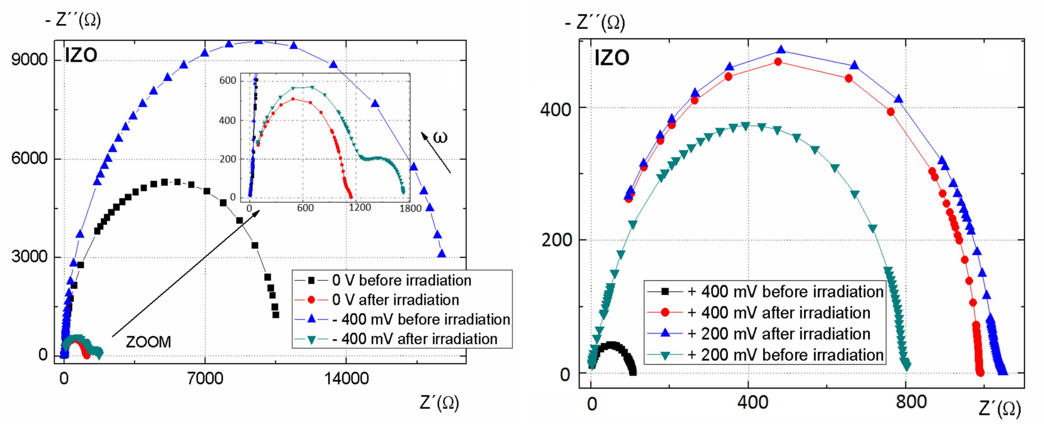


Figure 3. Measured (symbol) and the fitted (solid line) impedance spectra a), b) of ITO film for various DC bias in the dark for the sample before and after Xe irradiation.



a) b)

Figure 4. Measured (symbol) and the fitted (solid line) impedance spectra a), b) of IZO film for various DC bias in the dark for the sample before and after Xe irradiation.

For a more detailed assessment of the impact of Xe irradiation the analysis of AC equivalent circuit elements was made. Numerical analysis showed that the measured impedance data are best approximated using the equivalent circuit in figure 5. The circuit is formed by a series connection of resistance R_1 (series resistance), and two resistances R_2, R_3 connected parallel with constant phase elements (CPE), in figure 5 referred as P_1, P_2, resp. It can be assumed that one R-CPE parallel combination is related to the junction (space charge region) while the second R-CPE combination is related to the different interfaces traps [11]. The first parallel combination R_2-P_1 represented by a larger semicircle gradually disappears towards to forward bias (figure 3). It relates to the injection of charge carriers and the disappearance of space charge region. Second arc clearly visible at higher forward voltages is associated with the injection of minority carriers [12].

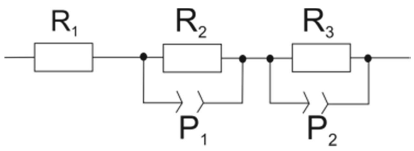


Figure 5. Proposed AC equivalent circuit of solar cell heterojunction.

For better illustration and quantification of the impact of irradiation the obtained fitted data for samples with ITO and IZO layer at DC bias 0 V are listed in the table 1. Leakage resistance R_2 was due to Xe radiation reduced from 12437 Ω to 1101.2 Ω for the sample with ITO layer and from 10616 Ω to 1036.5 Ω for the sample with IZO layer. The capacity P_2 (space charge region capacitance) was reduced by influence of Xe radiation as one can see in table 1. Parameter n is known as “non-ideality” Debye-like curve parameter. Parameter n is linked to capacitance CPE according to equation:

$$Z_{CPE} = 1/CPE(i\omega)^n, \quad (1)$$

exponent n = 1 for a purely capacitive load. The magnitude of exponent n suggest either drift process when n = 1 or diffusive process when n = 0.5. The CPE, in this case, has a dynamic origin and is related to the traps in the amorphous structure [13]. Detailed analysis of the CPE capacity exponent n and parallel AC equivalent circuit resistance on the applied DC bias enables the identification of transport processes in the structure. As can be seen by analyses of the parameter n, the change of space charge region properties due to exposure is negligible. Increase in P_3 capacitance and R_3 resistance

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Table 1. Fitted parameters of AC equivalent circuit obtained before and after Xe irradiation for samples with ITO and IZO layer obtained at zero bias.

ITO	R_2 (Ω)	R_3 (Ω)	P_2 (FS^{n-1})	n_2 (-)	P_3 (FS^{n-1})	n_3 (-)
before	12437	11.151	1.80E-08	0.99782	1.50E-07	0.92573
after	1101.2	75.052	1.18E-09	0.94703	1.88E-06	0.87532
IZO						
before	10616	41.939	1.77E-08	1	1.68E-07	0.87686
after	1036.5	100	7.19E-10	0.98292	9.82E-06	0.65481

indicate that the radiation induced structural defects were created. The parameter n_3 decreased after irradiation what can be simply interpreted as more markedly deviation from Debye-like behavior.

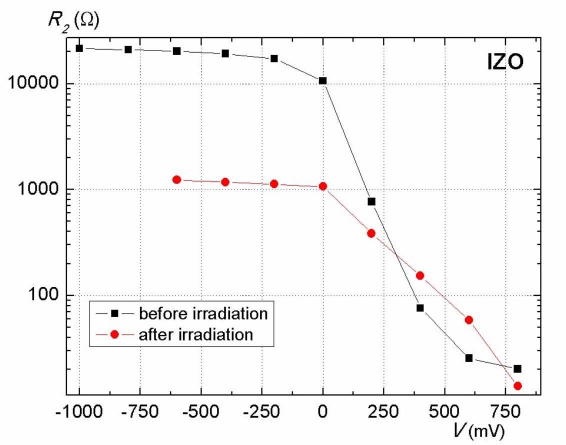

Figure 6. Parallel resistance R_2 as a function of applied bias before and after Xe irradiation for sample with IZO coating.

Figure 6, as a model example, shows the dependence of obtained parallel resistance R_2 on the DC bias voltage before and after irradiation for sample with IZO layer. It has been indicated that resistance R_2 is transport resistance and R_3 is recombination resistance. As is shown in figure 5, parallel resistance R_2 (and also parallel resistance R_3 not showed here) of AC equivalent circuit are at higher forward bias voltage strongly dependent on applied DC voltage. They go toward negligible values and behavior of the structure is controlled by series resistance. The effect of the Xe irradiation regarding R_3 was minimal for both study structures.

4. Conclusion

We have investigated the properties of experimental heterostructures with phosphorus doped silicon carbide films as emitter and ITO or IZO as antireflection film before and after the irradiation by Xe ions. RBS and ERD method were used for ITO and IZO films characterization. Impedance measurement and analysis in complex plane were performed before and after irradiation in order to identify influence of radiation on the electrical parameters of experimental solar cell heterojunction. Increasing of parallel conductivity due to the irradiation was observed. Increase of parallel capacitance and reduction of parameter n indicates creation of structural defects in amorphous layer.

Acknowledgements
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