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ELECTRICAL PROPERTIES OF SOLAR CELLS WITH A HETEROJUNCTION OF AMORPHOUS AND CRYSTALLINE SILICON IRRADIATED BY HEAVY XENON 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 $5 \times 10^{10} \mathrm{cm}^{-2}$. 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 electrophysical properties of the structures. On increasing the dose of irradiation the contribution of generation-recombination current from the amorphous part of silicon was growing. An increase in the density of interface traps and their electrical activity were observed in temperature dependent capacitance measurements in a wide frequency range of the measuring signal.

K e y w o r d s: Silicon HIT solar cell, amorphous-crystalline silicon heterostructure, heterojunction with intrinsic thin-layer, high-energy heavy ions irradiation, radiation hardness

1 INTRODUCTION

Solar cells based on silicon heterostructures belong to highly prospective photovoltaic devices [1, 2]. A significant advance 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) [3]. The reason is in its simplicity, low costs and a higher efficiency at higher temperatures in comparison with conventional cells [4]. Insertion of a thin intrinsic layer of amorphous silicon in the interface resulted in an improved efficiency of the cell [5]. Physical analyses of the mechanism of charge carriers transport through the a-Si:H(i)/c-Si interface were conducted in [6], in which the results of conductivity and capacitance measurements were analyzed and in [7] in which temperature dependent current-voltage measurements were employed. The full knowledge of the photovoltaic phenomenon requires understanding also the influence of elevated temperature and radiation. These factors may affect the performance of the solar cell markedly. Based on the results published in [8], in this contribution we pay attention to the radiation resistance of silicon heterostructures irradiated by heavy Xe ions. The intention was to simulate the impact of cosmic radiation upon the optical and electrical characteristics of the heterostructures. Thorough measurements of the radiation hardness of heterojunction solar cells were carried out in [9]. In this case, the influence was observed of proton irradiation with various doses on the distribution of radiation defects in the a-Si:H/c-Si and of their impact upon reduction of the minority carrier diffusion length L_{Dep}, shortening of the life time of minority carriers T_{ep} and in the final result on the reduction of the short circuit current I_{SC} and open circuit voltage $V_{0\mathrm{C}}$. The radiation damage was dominant in the region of crystalline silicon, while only negligible damage was observed in the amorphous part of silicon. The open question is to which extent the radiation affects degradation of the amorphous Si layer and the a-Si:H(i)/c-Si interface with the thin layer of intrinsic amorphous silicon. It has been shown that creation of the thin layer of intrinsic amorphous silicon lowers the trap density at the interface [10]. Hereby the adverse effect of interface trap-assisted recombination of charge carriers is suppressed. In the case of doped a-Si:H(n)/c-Si(p) structure the charge transport through the interface is accomplished by minority electrons and from this aspect it is given by the conduction band offset ΔE_c. The intrinsic amorphous layer of silicon presents a barrier for the flow of optically generated charge carriers. The positive role of the thin amorphous intrinsic silicon layer is derived from the ability to passivate the interface traps hereby suppressing the adverse effects of recombination of charge carriers at the interface. Analysis of the flow of charge carriers shows evidence of a strong effect of radiation defects both at the interface and in the bulk of the heterostructure.

2 EXPERIMENTAL

The charge flow through the HIT structure is strongly affected by the traps at the interface between amorphous and crystalline silicon. Therefore, attention has been

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paid to characterization of the a-Si:H(p)/a-Si:H(i)/c-Si(n) structure. The substrate was high-quality $< 111 >$ oriented p-type silicon doped by boron at concentration $1.6 \times 10^{21}\mathrm{m}^{-3}$. 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) of thickness 5 nm was deposited. Subsequently, samples are finalized by the deposition of 50 nm thick a-Si:H(n) to form the heterojunction emitter. The layers of amorphous silicon doped by phosphorus 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. Heterostructure a-Si:H(p) 50 nm/a-Si:H(i) 5 nm/c-Si(n) 525 μm was irradiated with heavy ions of Xe with energy 167 MeV at the IC-100 FLNR JINR cyclotron in the Laboratory of Nuclear Reaction of the Joint Institute for Nuclear Research, Dubna, Russia [11]. Ion beam homogeneity over the irradiated specimen surface was controlled using beam scanning in the horizontal and vertical directions and was better than 5%. The average Xe ion flux was less than $10^{9}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ to avoid significant heating of the targets mounted on water-cooled copper holders maintained at $25-30\,^{\circ}\mathrm{C}$. Vacuum was kept at 103 Pa. Samples with irradiation doses, AB1 $5\times10^{8}\mathrm{cm}^{-2}$, AB2 $5\times10^{9}\mathrm{cm}^{-2}$, AB3 $5\times10^{10}\mathrm{cm}^{-2}$ and non-irradiated control sample AB4 were investigated. For current and capacitance measurements, top emitter contacts with various areas of the gates were prepared by evaporation of aluminium. The bottom full area contact was created by evaporating aluminium onto the back side of silicon substrate. It is important to notice that prepared structures have not grid electrodes and thus not defined area, which is illuminated. Due to this the current measured under illumination is shown only with arbitrary unit (au). Output solar cell parameters are used just for comparison between samples measured under the same illumination conditions.

3 RESULTS AND DISCUSSION

Current-voltage ($I-V$) characteristics of irradiated samples measured under sun simulator are depicted in Fig. 1. A strong influence of the additional parasitic barrier for irradiated structures is indicated by the S-shape of the light $I-V$ characteristic. The possible reasons for formation of this parasitic barrier are the increase of the defect states in the amorphous layer which compensate phosphorous dopants and cause a shift of the Fermi level in the layer [12], a change of the band discontinuity between amorphous and crystalline silicon, which can vary with the hydrogen content in the a-Si:H layer [13], and a strong increase of the defect states at the a-Si:H/c-Si heterointerface [14]. The measured and extracted output photovoltaics parameters for studied samples are summarized in Tab. 1.

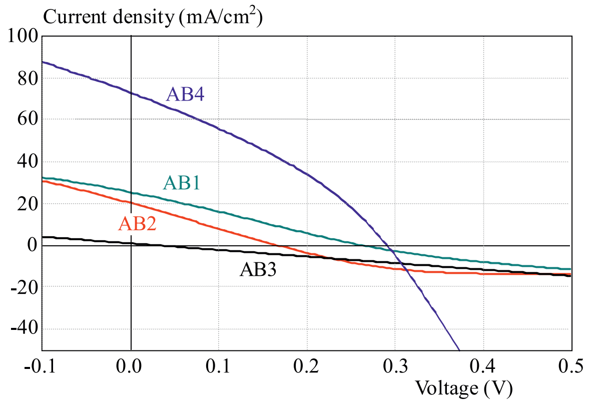

Fig. 1. Light current-voltage characteristics of samples irradiated by different doses of high-energy (167 MeV) Xe ions

The shape of the $I-V$ curves reveals strong degradation of the heterostructures after irradiation by 167 MeV Xe ions with doses from $5\times10^{8}\mathrm{cm}^{-2}$ to $5\times10^{10}\mathrm{cm}^{-2}$. Inhomogeneous distribution of radiation defects with a maximum in the depth of crystalline silicon and longitudinal range 20 μm was calculated using the TRIM software. It can be assumed that the enhanced density of electrically active defects in the active region of the heterojunction brings about a shortening of the effective diffusion length of minority charge carriers. This has been confirmed by the measured open circuit voltage, $V_{0\mathrm{C}}$ and short circuit current density, J_{SC}. Their magnitudes decrease with increased radiation doses. The samples of a-Si:H(p)/a-Si:H(i)/c-Si(n) with areas 1×1 cm for photovoltaic applications exhibited low values of the fill factor (FF) η given in Tab. 1. Degradation of heterostructures due to irradiation impaired the photovoltaic phenomenon markedly.

Table 1. Experimental values of typical output parameters for various irradiation doses of 167 MeV Xe ions

Sample	Dose (cm^{-2})	$V_{0\mathrm{C}}$ (mV)	J_{SC} (au)	FF (%)
AB 4	control	294	72.9	27.4
AB 1	5×10^{8}	271	25.8	20.4
AB 2	5×10^{9}	173	20.8	21.3
AB 3	5×10^{10}	48	1.7	23.5

A deeper analysis of the distribution of free charge carriers and of their transport in the vicinity of the a-Si:H/c-Si heterointerface can be provided by capacitance and admittance methods [15, 16]. We have carried out capacitance and admittance measurements onboth reverse and forward biased heterostructures at various frequencies of the measuring signal, from 1 kHz to 1 MHz. At a chosen value of the bias, the temperature was varied from 100 to 400 K. Figures 2,3 and 4,5, display the frequency dependences of capacitance and conductance at various temperatures measured at a forward bias voltage

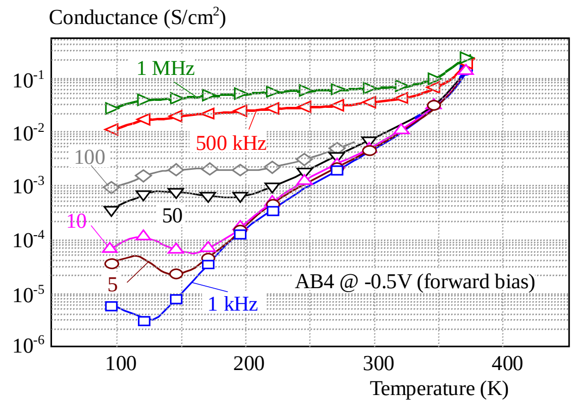

Fig. 2. Non-irradiated structure AB4 – conductance versus temperature

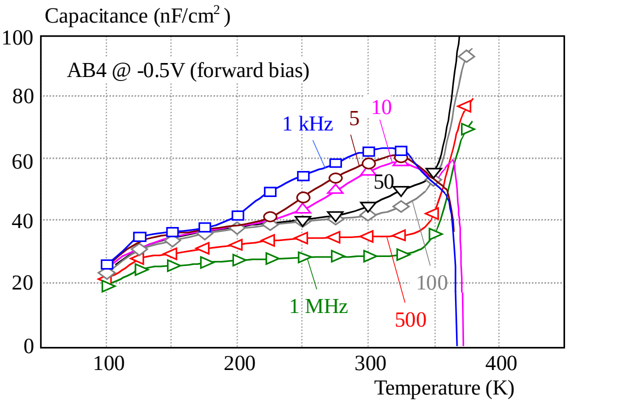

Fig. 3. Non-irradiated structure AB4 – capacitance versus temperature

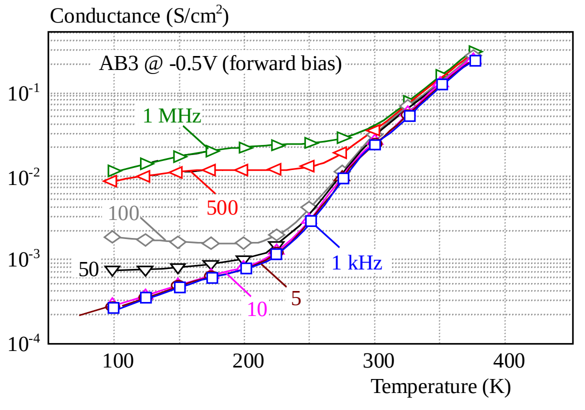

Fig. 4. Structure AB3 irradiated by 167 MeV Xe ions with a dose of $5 \times 10^{10}\mathrm{cm}^2$ – conductance versus temperature

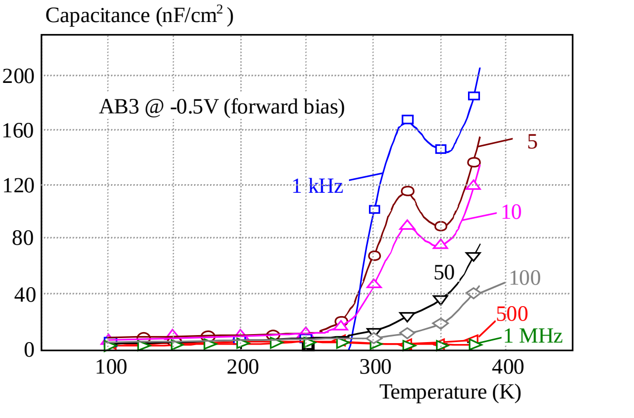

Fig. 5. Structure AB3 irradiated by 167 MeV Xe ions with a dose of $5 \times 10^{10}\mathrm{cm}^2$ – capacitance versus temperature

of - 0.5 V on the non-irradiated sample AB4 and on sample AB3 irradiated by the maximum dose $5 \times 10^{10}\mathrm{cm}^{-2}$, respectively. The growing temperature increases the conductance. On non-irradiated sample (Fig. 2), a maximum was observed at a temperature of 120 K. In the case of the irradiated sample such a maximum was not found (Fig. 4). Disappearance of the maximum conductance at lower temperatures is probably caused by activation of the phenomena of trapping and emission of free charge carriers due to the enhanced density of deep levels in the forbidden band. On increasing the frequency of the measuring signal the charge carriers contribute to conductivity more significantly.

The temperature dependence of capacitance characterizes the diffusion capacitance that expresses the change in the concentration of free charge carriers due to recombination. On lowering the measuring frequency the concentration of charge carriers with the ability to follow the measuring signal is higher and the capacitance increases (Fig. 3). High concentration of defect states at the heterointerface and in the bulk of the heterostructure results in a low value of the capacitance at low temperatures for the structure irradiated with a high dose (Fig. 5).

4 CONCLUSION

Radiation hardness of a-Si:H(p) 50nm /a-Si:H(i) 5nm /c-Si(n) 525 μm heterostructures after irradiation by various doses of heavy Xe ions was observed by current and capacitance measurements. The adverse impact of electrically active defects created both at the heterointerface and in the region of amorphous silicon strongly worsened the open circuit voltage and short circuit current of the cells. An increased dose of irradiation brought about a drop of the open circuit voltage and a marked loss of the photovoltaic phenomenon.

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