Influence of exposure with Xe radiation on heterojunction solar cell a-SiC/c-Si studied by impedance spectroscopy

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Abstract. The photovoltaic efficiency of heterostructures a-SiC/c-Si may be the same or even better in comparison with conventional silicon structures when suitable adjustment of technological parameters is realized. The main advantage of heterojunction formed amorphous SiC thin film and crystalline silicon compared to standard crystalline solar cell lies in high build-in voltage and thus a high open-circuit voltage. Solar cells can be exposed to various influences of hard environment. A deterioration of properties of heterostructures (a-SiC/c-Si) due to irradiation is examined in our paper using impedance spectroscopy method. Xe ions induced damage is reflected in changes of proposed AC equivalent circuit elements. AC equivalent circuit was proposed and verified using numerical simulations. Impedance spectra were also measured at different DC bias voltages due to a more detailed understanding correlation between Xe ions induced damage and transport phenomenon in the heterostructure.

1. Introduction
Hydrogenated amorphous silicon carbide (a-SiC:H) is a wide band-gap semiconductor, alternatively modified with other chemical elements, which forms heterojunction (HJ) with crystalline silicon. It could be relevant substitute for amorphous silicon (a-Si:H) and similarly its bandgap can be tuned over the wide range. Main advantage of amorphous SiC alloys lies in possibility to be deposited in low-temperature process chemical vapor deposition (CVD) [1]. The possibility of low-temperature fabrication processes is very interesting also for photovoltaics where structures with amorphous carbide thin films have important applications. Heterojunction of bulk silicon and amorphous a-SiC thin film represents an alternative to similar heterojunction a-Si/c-Si structure. Resistance against damage in hard environmental conditions is important advantage except for optical, thermal, electrical and mechanical properties of wide gap semiconductor a-SiC. Various forms of SiC are often exploited even in devices, eg sensors, exposed to hard radiation [2] due to high bandgap and high atomic displacement energies. Application of a-SiC in photovoltaic structure lead recently to the efficiency 25.6 % achieved on heterojunction structure, which makes this technology the most efficient among the silicon based solar cells [3]. The main advantage of heterojunction formed amorphous SiC thin film and crystalline silicon compared to standard crystalline solar cell lies in high build-in voltage and
thus a high open-circuit voltage [4]. Taking into account external influences PV device has to be evaluated in more complex way and all aspects of its performance shall be considered [5].

Chemical bonds in SiC are primarily covalent but small percentage of them has ionic character. The reaction of particle, like neutrons, protons or ions, flux with solid matter is through elastic collision with atomic nuclei, often resulting in the damage of crystalline structure. It is important to emphasis that some structural defects in SiC are charged, which is related to the mentioned fact that SiC is a wide band gap semiconductor [6].

We have studied heterojunction solar cell device composed of thin layer a-SiC deposited on silicon substrate. ITO layer was used for antireflection and passivation purpose which also offers adequate transmittance and high conductance.

In order to estimate the ability to withstand hard environmental condition we have studied the influence of Xe ions bombardment on prepared samples a-SiC/c-Si with ITO at the front surface. The AC electrical response and complex impedance, which showed to be convenient tool, have been investigated.

2. Experimental

The heterojunction structures were fabricated on p-type Si (100) 1 x 1 cm wafers. Phosphorus doped silicon carbide film as emitter was deposited by PECVD technology using silane (SiH4 -10 sccm), methane (CH4 -3 sccm), hydrogen (H2 -100 sccm) and PH3 (2.0 vol.% in H2, 15-30 sccm), gas as precursors. ITO (indium oxide/tin oxide 90/10 wt. %) film was RF magnetron sputtered on top of the different P doped a-SiC:H(n) films. The thickness of the deposited ITO films was kept at 100 nm. Photolithography and lift off technique was used for Al grid preparation as top contact of solar cell structure and bottom Al ohmic contact was prepared by Al evaporation. Irradiation of structures with Xe ions to total fluency 5x10¹¹ cm⁻² was performed at room temperature in the IC100 accelerator at JINR Dubna, Russia. Impedance spectra were measured by the Agilent LCR Meter 4284A. The amplitude of AC signal voltage was kept at 25 mV which maintains the linearity of the response. The real and imaginary components of the impedance (Z' and Z'') were measured at 100 Hz to 1 MHz frequency range. DC bias was varied in the interval from - 0.8 V to + 0.7 V.

3. Results and discussion

Fig. 1 shows the obtained impedance data of the HJ structure under reverse and forward bias before and after Xe irradiation. The obtained plot has semicircular shape and are composed from superposition of two semicircles (two relaxation processes – better recognizable after irradiation). The diameter of the circles depends on the applied DC bias. Shunt resistance (diameter of semicircle) of HJ structure was significantly reduced under reverse bias conditions when Xe ion irradiation was brought into effect, as one can see in Fig. 1a.

The behavior under forward bias condition is different (Fig. 1b).

![Figure 1. Obtained impedance spectra for forward and reverse conditions obtained in the dark at the room temperature.](image-url)
Irradiation by Xe ions results in increasing of conductivity. This result correlates with DC measurement. The influence of Xe bombardment is demonstrated on current-voltage characteristic shown in Fig. 2.

**Figure 2.** Example of I-V characteristic under forward bias of structure before and after Xe ions irradiation.

The increased fluency of Xe ions results in increased structure conductivity. The parallel resistance of HJ structure is combination of the shunt and dynamic resistance. Dynamic resistance of junction under forward DC bias reaches incomparable smaller value of resistance than the shunt resistance. For this reason, in forward bias conditions only dynamic resistance is contributing to the total cell resistance. Dynamic resistance decreases with increased forward bias but remains independent of frequency within certain interval of frequencies and start decrease toward series resistance value at higher frequencies [7].

Modeling of obtained impedance data by AC equivalent circuit was necessary for the understanding of processes before and after Xe irradiation inside heterostructure. Xe ions induced damage reflected in changes of AC equivalent circuit elements and equivalent circuit had to be modified. Alternative AC equivalent circuits were proposed and verified using numerical simulations. Impedance spectra were also measured at different DC bias voltages due to a more detailed understanding the correlation between ions induced damage and transport phenomenon in the heterostructure. As high energy ions penetrate into a solid, those ions can deposit kinetic energy in two processes: electronic excitation and ionization, and nuclear collision. Kinetic energy transfer between penetrating ions and target atoms takes place through collective processes of nuclear collisions in a displacement [8]. Moreover generated defects can be charged.

AC equivalent circuit, before and after Xe irradiation which best fits the obtained impedance data is shown in Fig. 3. Series resistance $R_1$ is related to resistance of contacts and electrode system (grid on top and whole area bottom) in both cases a) and b). Parallel combination of resistance $R_2$ (transport resistance) and capacitance $C$ (Fig. 3a) is linked to space charge region of the pn hetero-junction situated within the structure. Second combination of resistance $R_3$ (recombination resistance) and constant phase element (CPE) $P_1$ (Fig. 3a) should be associated with traps and defects in the structure [7, 9]. The parallel combination of $R_2$ and $C$ is associated with semicircle in left part of Nyquist plot thus, the area of higher frequencies. Semicircle assigned to $R_2$ and $P_1$ (Fig. 3a) in lower frequency region is associated with internal charge transfer including accumulation $P_1$ and recombination $R_3$. As can be seen, the result of Xe exposure lead to change of electric behaviour of structure and necessarily the equivalent circuit had to be modified (Fig. 3b) as a result of disorders caused due to Xe irradiation of thin film structure.
The behavior of respective equivalent circuit elements before and after irradiation is shown on Fig. 4 and 5. Fig. 4 shows the dependence of obtained parallel resistances $R_2$ and $R_3$ for the applied DC bias voltage before and after Xe irradiation. As can be seen in Fig.4a, parallel resistors of AC equivalent circuit have a standard behavior before the Xe irradiation. The resistance decreases with increasing DC voltage. Parallel resistance $R_2$ is strongly dependent on the applied bias mainly at forward voltages. As for $R_2$, it is similar before and after irradiation. Parallel resistance $R_3$ of modified circuit is practically independent on applied voltage after irradiation, shown in Fig. 4b, what indicates the deterioration of pn junction which we suppose to be governed more by ohmic process. Series resistance is an important parameter of photovoltaic structure governing the power output. But series resistance $R_1$ is not influenced by Xe bombardment in any remarkable way.

The dependences of numerically obtained values of capacitive elements at forward and reverse bias are presented in Fig. 5. The main contribution to parallel capacitance, under the reverse bias conditions is the depletion layer capacitance.
At higher forward bias voltages, the depletion region associated with space charge region is disappearing (the capacitance C is not more dominant) therefore, the equivalent circuit evolves to a circuit of parallel $R_1$ and constant phase element $P_1$ in series with $R_1$. The increase of $P_1$ at positive biases before irradiation is related to the injection of minority charge carriers. Constant phase element was introduced into the equivalent AC circuit due to the properties of the structure (amorphous, disordered structure with the existence of structural defects). Introduction of constant phase element is in cases when the experimental data reveal a significant deviation from this simple R-C behavior, becoming apparent in a deformation and broadening of the impedance semicircle. A common phenomenological approach describes these broadened semicircle by a parallel connection of resistor $R$ and a CPE.

Replacing the capacitor by the CPE but preserving the resistor in the circuit has the practical advantage that the DC conductivity can still be determined by directly fitting the parameter $R$ [10].

Electrical impedance of CPE can be expressed as

$$Z_{CPE} = Y_0^{-1}(j\omega)^{-n}$$

where $Y_0$ represents CPE coefficient and $n$ represents the character and an ideality of the distribution of relaxation times, $\omega$ is angular frequency [11].

The Xe bombardment led to change of conductive processes which is reflected in modified equivalent circuit. The circuit with two CPE’s after the Xe irradiation was proposed. In case of CPE capacitance $P_1$ increase of capacitance with increasing DC voltage was observed as shown in Fig. 5b while constant phase element $P_2$ is independent on applied voltage after Xe bombardment.

4. Conclusion
The solar heterojunction structure a-SiC/c-Si with used transparent conductive layer ITO which has been exposed to Xe irradiation was the object of research. Impact of the Xe radiation on electrical transport processes was monitored and evaluated by electrical impedance spectroscopy. AC equivalent circuit as the result of fitting the obtained impedance data was proposed and served to describe the electrical processes which result from radiation exposure. The most serious consequence of Xe exposure was significant increase of total resistance under forward bias which would lead to poor photovoltaic properties (not discussed at this place). The structural defects induced by Xe particles radiation affect also trapping mechanism what is illustrated by the influence of radiation on CPE included into equivalent circuit.

Acknowledgments
This work was supported by the Slovak Research and Development Agency under the contract No. APVV-0443-12 and by the Scientific Grant Agency of the Ministry of Education of the Slovak Republic and of the Slovak Academy of Sciences Project VEGA 1/0651/16. This paper is also the result of the project implementation: Finalizing of the National Centre for Research and Application of renewable Energy Sources, ITMS: 26240120028, supported by the R&D Operational Programme funded by the ERDF.

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