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 $5 \times 10^{10}$ cm$^{-2}$ to $5 \times 10^{10}$ 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.

**Key words:** 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/i/c-Si and of their impact upon reduction of the minority carrier diffusion length $L_{dp}$, shortening of the life time of minority carriers $T_p$ and in the final result on the reduction of the short circuit current $I_{SC}$ and open circuit voltage $V_{OC}$. 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 $\Delta E_c$. 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 thereby 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
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 × 10^{19} \text{m}^{-3}. The thickness of Si wafers was 525 \mu \text{m}.
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 sil-
icon were deposited by plasma enhanced chemical vapour
deposition (PECVD) in the Laboratory of Photovoltaic
Materials and Devices, TU Delft in the Netherlands. Het-

erostructure a-Si:H(p) 50 nm/a-Si:H(i) 5 nm/c-Si(n) 525
\mu \text{m} was irradiated with heavy ions of Xe with energy 167
MeV at the IC-100 FLNR JINR cyclotron in the Labo-
matory of Nuclear Reaction of the Joint Institute for Nu-
clear Research, Dubna, Russia [11]. Ion beam homogene-
ity of the irradiated specimen surface was controlled
using beam scanning in the horizontal and vertical direc-
tions and was better than 5%. The average Xe ion flux
was less than 10^{18} \text{cm}^{-2} \text{s}^{-1} to avoid significant heating of
the targets mounted on water-cooled copper holders
maintained at 25 – 30 °C. Vacuum was kept at 103 Pa.
Samples with irradiation doses, AB1 5 × 10^{10} \text{cm}^{-2}, AB2
5 × 10^{10} \text{cm}^{-2}, AB3 5 × 10^{10} \text{cm}^{-2} and non-irradiated con-
trol sample AB4 were investigated. For current and ca-
pacitance measurements, top emitter contacts with var-
ious 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 sub-
strate. 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). Out-
put 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 bar-
rier 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 be-
tween 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 summa-
rized in Tab. 1.

The shape of the I–V curves reveals strong degrada-
tion of the heterostructures after irradiation by 167 MeV
Xe ions with doses from 5 × 10^{8} \text{cm}^{-2} to 5 × 10^{10} \text{cm}^{-2}.
Inhomogeneous distribution of radiation defects with a
maximum in the depth of crystalline silicon and longitu-
dinal range 20 \mu \text{m} was calculated using the TRIM soft-
ware. It can be assumed that the enhanced density of
electrolytically active defects in the active region of the het-
erojunction brings about a shortening of the effective dif-
fusion length of minority charge carriers. This has been
confirmed by the measured open circuit voltage, \text{V}_{\text{OC}}
and short circuit current density, \text{J}_{\text{SC}}. Their magnitudes de-
crease with increased radiation doses. The samples of a-
Si:H(p)/a-Si:H(i)/c-Si(n) with areas 1 × 1 cm for photo-
voltaic applications exhibited low values of the fill factor
(FF) \eta given in Tab. 1. Degradation of heterostructures
due to irradiation impaired the photovoltaic phenomenon
markedly.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Dose (cm(^{-2}))</th>
<th>\text{V}_{\text{OC}} (mV)</th>
<th>\text{J}_{\text{SC}} (au)</th>
<th>FF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB 4</td>
<td>control</td>
<td>294</td>
<td>72.9</td>
<td>27.4</td>
</tr>
<tr>
<td>AB 1</td>
<td>5 × 10^{8}</td>
<td>271</td>
<td>25.8</td>
<td>20.4</td>
</tr>
<tr>
<td>AB 2</td>
<td>5 × 10^{9}</td>
<td>173</td>
<td>20.8</td>
<td>21.3</td>
</tr>
<tr>
<td>AB 3</td>
<td>5 × 10^{10}</td>
<td>48</td>
<td>1.7</td>
<td>23.5</td>
</tr>
</tbody>
</table>

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 ca-
pacitance and admittance measurements on both reverse
and forward biased heterostructures at various frequen-
cies 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 fre-
quency dependences of capacitance and conductance at
various temperatures measured at a forward bias voltage
of -0.5 V on the non-irradiated sample AB4 and on sample AB3 irradiated by the maximum dose $5 \times 10^{10}$ 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) 50 nm /a-Si:H(i) 5 nm /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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REFERENCES


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